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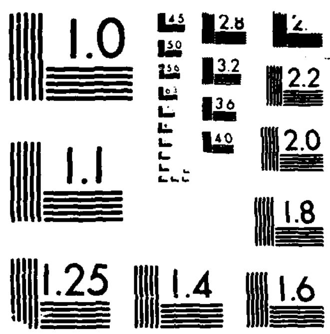

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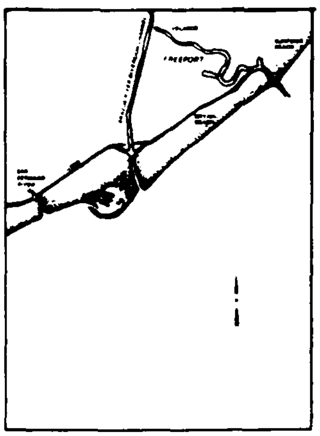

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MISCELLANEOUS PAPER CERC-88-7

ANALYSIS OF SEDIMENT TRANSPORT IN THE BRAZOS RIVER DIVERSION CHANNEL ENTRANCE REGION

by

M. Leslie Fields, Lee L. Weishar, James E. Clausner

Coastal Engineering Research Center

DEPARTMENT OF THE ARMY
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May 1988

Final Report

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

A combined office and field study was conducted to evaluate the feasibility of constructing a navigation channel in the Brazos River Diversion channel (BRDC). The evaluation was made through an analysis of existing data and a computation of shoaling rates. The office study consisted on an evaluation of the shoaling history of the area, which was determined through quantification on an evaluation of the shoaling history of the area, which was determined through quantification of shoreline migration rates, and volumetric changes in the growth of the BRDC delta. Nearshore available longshore sediment transport quantities and rates were determined using Littoral Environment Ovservation (LEO) data. A two-dimensional (2-D) laterally averaged numerical model was used to predict sediment transport in the BRDC for the proposed channel dimensions. A second 2-D numerical-wave refraction/diffraction model was used to predict wave propagation over the Brazos River ebb-tide delta and adjacent regions. Field data utilized to run the numerical models

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19. ABSTRACT (Continued).

consisted of water surface elevations, current velocities, salinities, suspended sediment concentrations, nearshore sediment samples, and bathymetric survey data. Considerations of the hydraulics in the lower BRDC suggest sediment transport occurs on a seasonal basis, resulting in periodic flushing and shoaling conditions. Shoaling rate calculations for the proposed channel dimensions of 12-ft deep by 125-ft wide, with 6-ft overdredging predict an annual maintenance dredging requirement of 735,000 cu yd, with an estimated project duration of approximately 4 months.

PREFACE

The study described herein was conducted from August 1984 through February 1985 at the US Army Engineer Waterways Experiment Station (WES) by the Coastal Engineering Research Center (CERC) and Hydraulics Laboratory (HL), for the US Army Engineer District, Galveston (SWG).

The report was prepared by CERC personnel Ms. M. Leslie Fields and Dr. Lee L. Weishar under the supervision of Mr. H. Lee Butler, Chief, Research Division, and Mr. James E. Clausner under the supervision of Mr. Thomas W. Richardson, Chief, Engineering Development Division. Hydraulics Laboratory participation was provided by Mr. Michael J. Trawle, under the supervision of Mr. W. H. McAnally Jr., Chief, Estuaries Division. Technical editing and drafting support were provided by the Information Products Division, a branch of the Information Technical Laboratory.

This study was conducted under the general direction of Dr. J. R. Houston, Chief, CERC, and Mr. F. A. Herrmann, Jr., Chief, HL.

COL Dwayne G. Lee, CE, is the present Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic inches	16.38706	cubic centimetres
cubic yards	0.7645549	cubic metres
degrees (angle)	0.1745329	radians
feet	0.3048	metres
feet per mile	0.1893935	metres per kilometres
foot-pounds (force)	1.355818	metre-newtons or joules
inches	2.54	centimetres
miles (US nautical)	1.852	kilometres
miles (US statute)	1.609347	kilometres
pounds (force)	4.448222	newtons
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square metres
square inches	6.4516	square centimetres
square miles	2.589998	square kilometres
square yards	0.8361274	square metres
yards	0.9144	metres

ANALYSIS OF SEDIMENT TRANSPORT IN THE BRAZOS RIVER DIVERSION CHANNEL ENTRANCE REGION

PART I: INTRODUCTION

Background

1. This study was conducted by the US Army Engineer Waterways Experiment Station (WES) Coastal Engineering Research Center (CERC) for the US Army Engineer District, Galveston (SWG), to determine the feasibility of dredging the Brazos River Diversion Channel (BRDC) to provide continuous navigable depth. The proposed project design includes that of a channel dredged to a 12 ft* depth from its intersection with the Gulf Intracoastal Waterway (GIWW) to the 12 ft contour in the Gulf of Mexico (Figure 1). Such a project would benefit vessels currently berthed 8.2 miles upstream from the GIWW. This project is being conducted under the small projects program authorized under Section 107 of the River and Harbor Act of 1960, as amended.

2. As an initial step in assessing the feasibility of the BRDC project, a reconnaissance report was prepared by SWG describing the project's various features (US Army Engineer District, Galveston, unpublished report**). The selected plan consists of a channel 12 ft deep and 125 ft wide, extending from the intersection of the BRDC with the GIWW into the Gulf of Mexico. The proposed channel would be 12,400 ft long, including 5,000 ft of channel in the open Gulf. The plan requires a nominal channel depth of 12 ft, with 6 ft of overdredging, creating an effective depth of 18 ft. A pipeline dredge would be used for channel dredging, with disposal of material on the Gulf beach directly southwest of the Brazos River mouth (Figure 1). Proposed maintenance dredging would be conducted by using a hopper dredge that would dispose of material in existing Freeport Harbor offshore disposal sites (Figure 1).

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* A table of factors for converting non-SI units or measurement to SI (metric) units is presented on page 6.

** US Army Engineer District, Galveston. "Brazos River Diversion Channel: Reconnaissance Report," (unpublished report), Galveston, Tex.

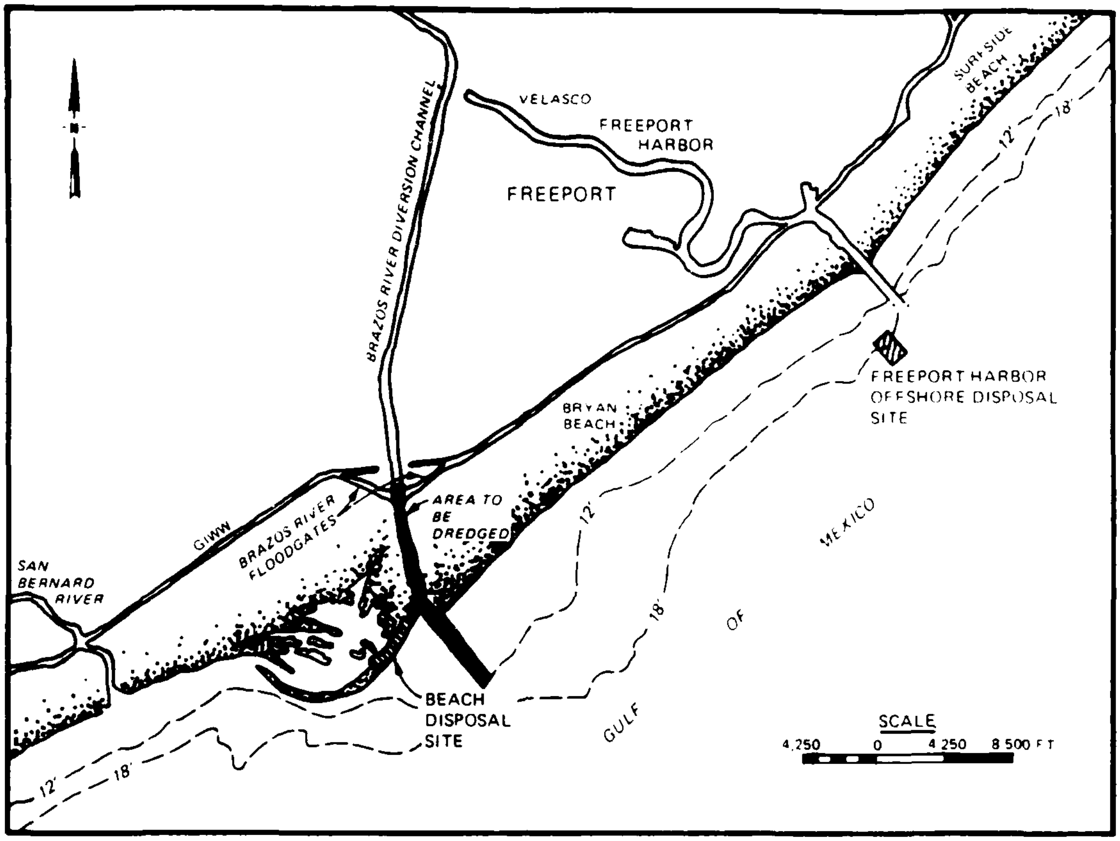

Figure 1. Project plans for the BRDC

Current Study

3. This report describes a combined office and field study conducted to evaluate the feasibility of the BRDC project through an analysis of existing data and the computation of shoaling rates. The project's feasibility and cost are dependent on the volume of dredged material required for initial construction and annual maintenance, the depth of advance maintenance dredging, the duration of project depth, and the frequency of maintenance dredging. Each of these factors is dependent upon shoaling rates in the project's vicinity.

4. As part of the office study, historical shoaling rates and directions of sediment movement were determined through an analysis of available reports, surveys, and aerial photographs. Volumetric calculations were made on the BRDC delta by using available bathymetric charts. The office study included an estimation of longshore transport rates that were calculated by using the Littoral Environment Observations (LEO) collected on nearby beaches.

In addition, a linear numerical model was used to evaluate the combined effects of wave refraction and diffraction at the mouth of the BRDC under varying wave conditions. A second numerical model was used to determine the hydraulic characteristics of the diversion channel. The field study included a detailed bathymetric survey of the BRDC delta and channel, a sediment sampling program to determine ambient grain sizes, and tidal and current velocity measurements in the BRDC. Shoaling rates for the proposed project were calculated using the above-mentioned data.

PART II: STUDY AREA

History of Brazos River Diversion Channel

5. The BRDC is located on the Gulf Coast near Freeport, Texas, in the southern part of Brazoria County (Figure 2). The area is approximately 50 miles southwest of Galveston, Texas.

6. Prior to construction of the diversion channel, the Brazos River entered the Gulf of Mexico approximately 2 miles east of Freeport. Because the Brazos is one of the few Texas rivers that empties directly into the Gulf, shipping interests saw the necessity of developing the lower part of the river as a harbor. In 1850, a channel was dredged from the Gulf to a turning basin upstream. The heavy sediment load of the Brazos River resulted in rapid

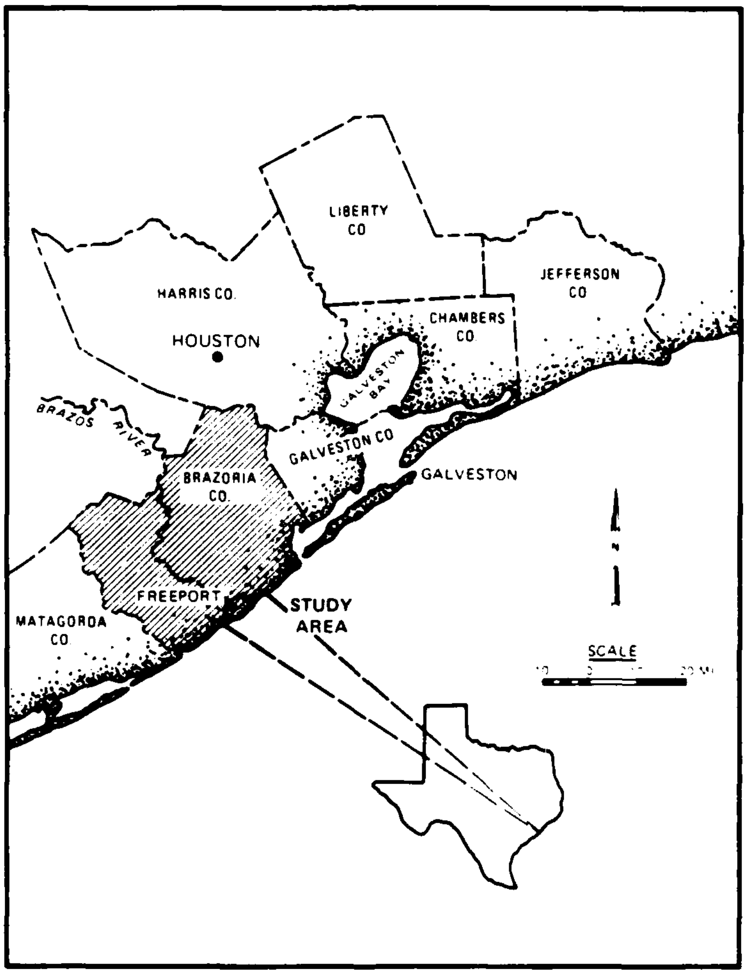

Figure 2. Study area location

shoaling of the channel which required continual maintenance dredging. Local interests began work on two parallel jetties in 1881, but the project was abandoned in 1886 due to a lack of funds and rapid deterioration of the jetties. The US Army Corps of Engineers resumed work on the project in 1889 and completed two rubble-mound jetties protecting the harbor's entrance in 1896.

7. Despite construction of the jetties, heavy sedimentation associated with frequent flooding of the Brazos River created navigation hazards and excessive maintenance dredging was required. As a result, the Brazos River was diverted by the Corps of Engineers in 1929 at a point 7.5 miles upstream from the river's mouth. A diversion channel was dredged from this point in a south-southwest direction to the Gulf, relocating the mouth 6.5 miles from the original location at Freeport Harbor. After construction of the BRDC, Freeport Harbor became entirely tidal and as a result of the diversion project it presently operates with an average annual dredging rate of 1,140,000 cu yd. It was intended that the BRDC would absorb the sediment load of the Brazos River, and, therefore, no maintenance dredging was planned for the diversion channel. The GIWW crosses the BRDC 7,000 ft upstream from its mouth. Tidal and fluvial flows into the GIWW are controlled by two flood gates constructed and controlled by the Corps of Engineers.

Tide Range and Level

8. The average durinal tidal range along the Texas Gulf Coast is approximately 2 ft. Mason (1981) used data from the National Ocean Service (NOS) gages at Freeport, Galveston, and Sabine Pass to study the seasonal variability in monthly mean diurnal tidal ranges and tidal levels between 1955 and 1975. He found that maximum monthly tidal ranges (daily higher high water minus lower low water) occur at the solstices in June and December and minimum ranges occur at the equinoxes during September and March (Figure 3). His study showed that the trend of water level fluctuations is out of phase with the trend of tidal range. Maximum water levels (average of hourly water levels over some time period) occur in May and September during periods of onshore winds (Figure 4). Minimum water levels occur in February and July.

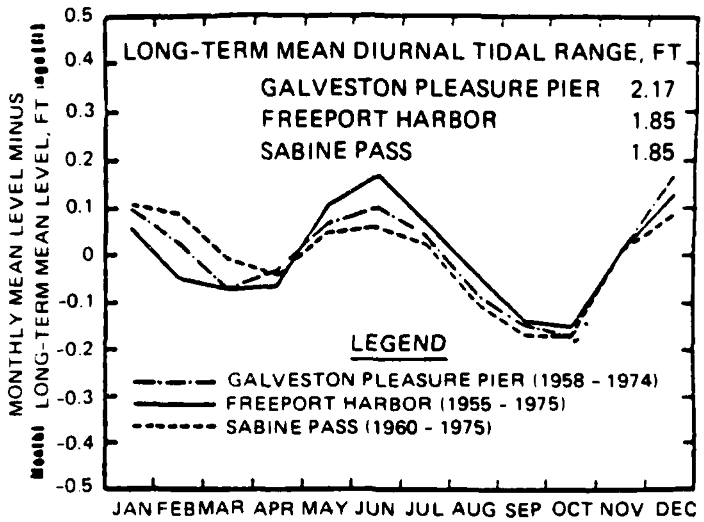

Figure 3. Long-term monthly mean tidal range variability (from Mason 1981)

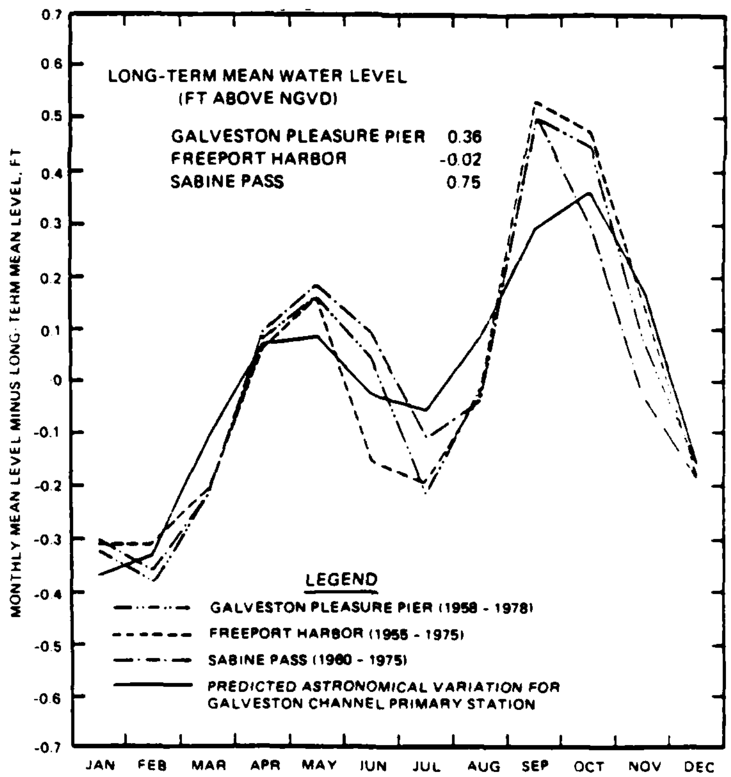

Figure 4. Long-term monthly mean water level variability (from Mason 1981)

Long-Term Variability in Tide Level

9. Long-term trends in mean sea level have been studied by Morton (1974) and Mason (1981). Both studies show a gradual rise in the mean sea level at Galveston for the period 1909 to 1975 with rapid increases in 1940 and 1970 (Figure 5). The patterns of relative water level rise for three Texas Gulf Coast locations are shown in Figure 6. The three sites show similar trends between 1960 and 1970 with considerable variation between 1970 and 1975. Mason (1981) uses these data to suggest that much of the recent rise in sea level is due to increased and localized subsidence. Marmer (1951) studied sea level records from several Gulf Coast stations and found that the rates of

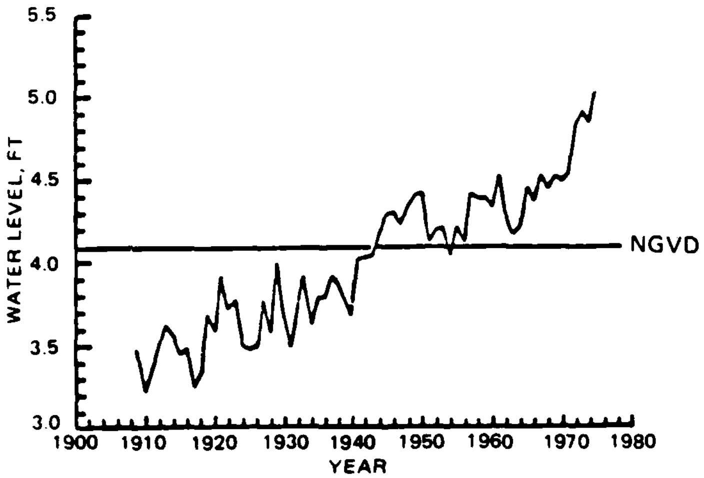

Figure 5. Variation of annual mean water level, Galveston Channel (from Mason 1981)

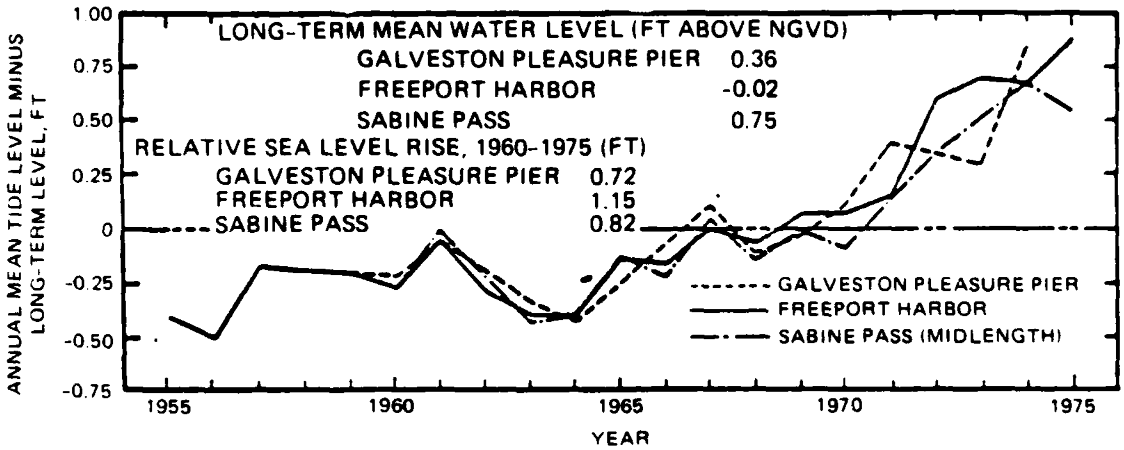

Figure 6. Historical variation in mean water level (from Mason 1981)

sea level rise were not constant throughout the Gulf. He speculated that the differences were due to localized subsidence. Summary of Synoptic Meteorological Observations (SSMO) data for the Texas Gulf Coast are shown in Figure 7.

Winds

10. Prevailing winds along the Texas Gulf Coast are from the south and southeast. During the winter, strong frontal systems produce dominant winds from the north. The yearly average wind rose shows that 31 percent of the winds come from the southeast, 19 percent from the south, and 15 percent from the north (US Army Engineer District, Galveston (in preparation)).

Wave Climate and Littoral Drift

11. The deepwater wave rose for the Texas Coast shows that 26 percent of the waves approach from the southeast, and 20 percent from the east (Figure 7, Bretschneider and Gaul 1956). Thompson (1977) calculated an annual significant wave height of 1.5 ft and a mean period of 6 sec at Galveston. Estimates of longshore transport rates based on LEO indicate a net southwest transport through the study area. This is in agreement with longshore transport calculations made by others (Carothers and Innis 1960, Seelig and Sorensen 1973a, US Army Engineer District, Galveston (in preparation)).

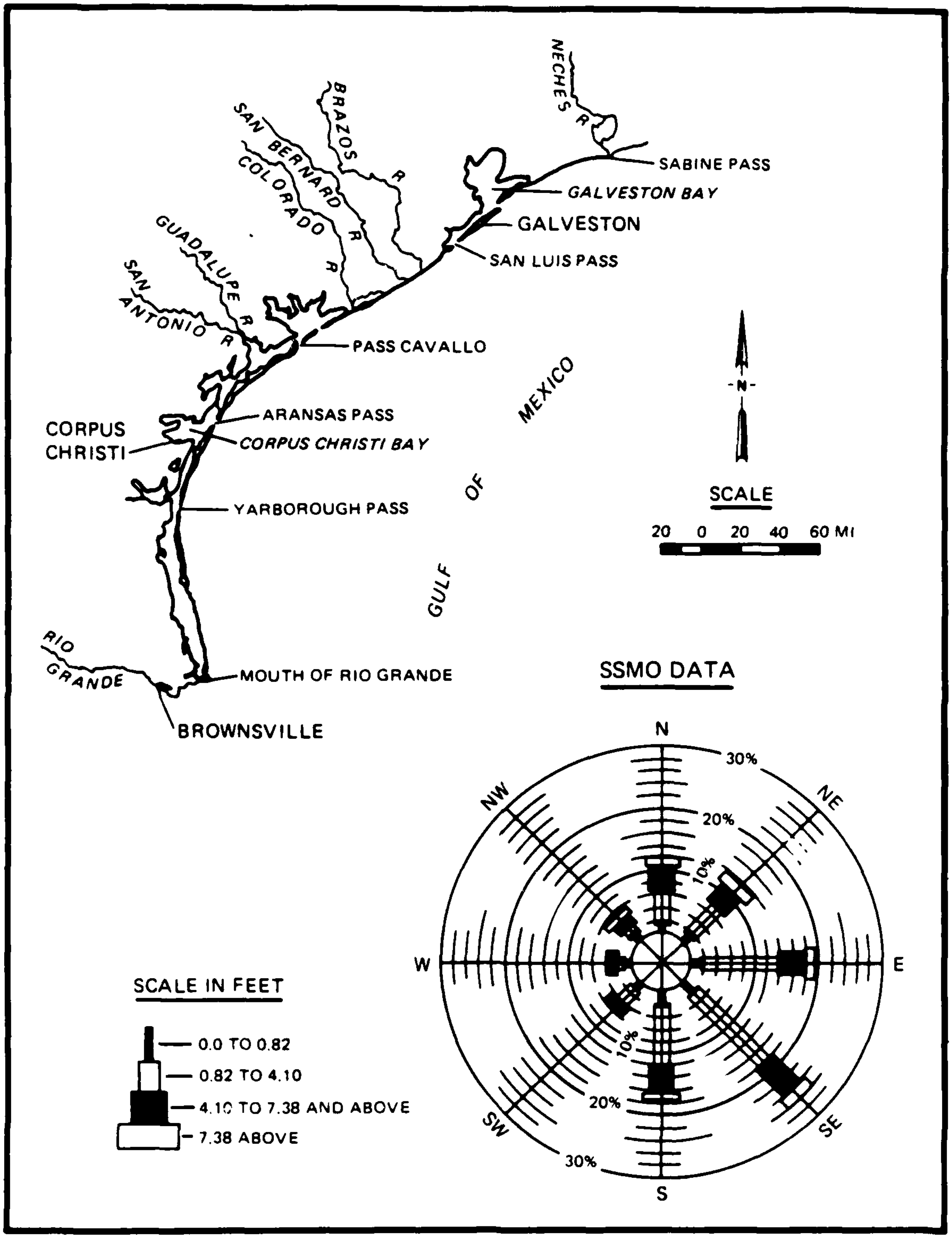

Figure 7. SSMO deepwater wave height versus wave direction annual statistics

PART III: PREVIOUS WORK

Design and Condition Reports, Freeport Harbor and BRDC

12. The first recorded plans to establish a permanent harbor at the mouth of the Brazos River by the construction of jetties were given by Wisner (1891). The jetties were completed in 1899, creating the Federal project known as Freeport Harbor, Texas. Fox (1931) published an historical account of the preliminary studies and designs for the construction of a diversion channel rerouting the Brazos River 6.5 miles southwest of the original mouth. The BRDC was completed in 1929 by the Corps of Engineers. Both of these reports provide useful information on the conditions at the mouth of the Brazos River, prior to and during construction of these navigation projects.

Sedimentological and Geological Studies

13. US Army Corps of Engineers bathymetric surveys at the mouth of the Brazos River indicate that an offshore delta began to form immediately after construction of the BRDC. Aerial photos and NOS hydrographic charts show that the subaqueous portion of the delta grew rapidly, with extensive subaerial deposits forming on either side of the channel.

14. An extensive account of the BRDC delta was produced by Odem (unpublished report*). His report included an analysis of bathymetric and shoreline changes, from which he concluded that subaerial delta growth extended 2 miles into the Gulf and that 75 percent of the deltaic material was added between 1942 and 1953. A study of grab samples collected from the BRDC and adjacent beaches, and short cores taken across the delta, led Odem (1953) to suggest that the Brazos River has a high sediment discharge during the spring, with fluvial deposition occurring seaward of the mouth and to the southeast. During the winter months, much of this material is redistributed southwest of the river mouth.

15. Nienaber (1963) collected surface grab samples over a 750-square-mile area offshore from the BRDC and Freeport Harbor. The samples were taken

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* Odem, W. I. 1953 (unpublished report). "Delta of the Diverted Brazos River of Texas," M.S. thesis, University of Kansas, Lawrence, Kansas.

along five transects normal to shore, extending from the shoreline to water depths of 120 ft. His report shows that the delta was composed of poorly sorted sandy topset beds, extensive foreset beds of sand and silt which grade downward (seaward) into mud and clay, and thin bottomset beds composed of clay. Nienaber (1963) suggested that the seaward limit of deposition from the Brazos was 10 to 17 miles offshore in water depths of 60 to 70 ft.

16. A field trip guide prepared by Bernard, Le Blanc, and Majors (1976) on the "Recent Sediments of Southeast Texas" included a section on the sedimentology of the BRDC delta. The guide described an offlap sequence of deltaic deposits found within a series of cores taken from subaerial portions of the delta. The sequence is composed of progressively younger strata deposited in layers offset seaward, and is indicative of progradation of the BRDC delta. A set of six cores collected in 1972 and 1973 by the Civil Engineering Department, Texas A&M University, are described by Seelig and Sorensen (1973a). The cores were taken from 4 to 35 miles offshore of the Brazos delta. They show that a 2-in.-thick sand layer underlain by several feet of fine silt and clay covers a large portion of the offshore area. Each of these studies on the sedimentology of the BRDC delta was useful in tracing the growth and development of the delta, and in characterizing the relative influences of fluvial and littoral sediment load.

Hydraulic Studies

17. Two separate publications on the hydraulics of the BRDC have been prepared by the US Geological Survey (USGS) in cooperation with the Texas Water Development Board (Grozier and Yost 1959, Johnson, Rawson, and Smith 1967). Field data for both studies were collected within the lower 3 miles of the BRDC. The magnitude and direction of velocity and the variations in flow through a complete tidal cycle were determined for each study. In addition, salinity was measured and river discharge was calculated by using the current velocity data.

18. Water discharge and suspended sediment discharge for the Brazos River recorded as monthly and yearly totals by the Texas Water Development Board (formerly the Texas Board of Water Engineers) are given in Stout, Bentz, and Ingram (1961), Adey and Cook (1964), Cook (1967, 1970), and Mirabel (1974). Brazos River discharge records are also published annually by the

USGS in volumes entitled "Water Resources Data for Texas, Part 1, Surface Water Records."

19. Mathewson and Minter (1976) discuss the relationship between water resource development in the Brazos River Basin and the rate of erosion at Sargent Beach, which is approximately 16 miles west of the BRDC. Their results indicate that dam and reservoir development along the Brazos River between 1937 and 1973 has reduced the frequency of high discharge events and physically trapped much of the sand previously carried to the coast. They estimated the total amount of sand supplied to the system by the Brazos River during this 37-year period to be 1,931 million cu ft. Based on sediment discharge data prior to modification of the Brazos River, an estimated 1,808 million cu ft of material was lost due to reservoir construction. Their figures suggest that this loss resulted in an increase in the shoreline recession rate at Sargent Beach from 13 ft per year to 20 ft per year. Based on these figures, Mathewson and Minter (1976) calculated a net retreat of 740 ft for Sargent Beach for the period 1937 to 1973. These reports provide data useful in evaluating the hydraulics of the Brazos River and for determining the effects of sediment load variations on shoaling rates at the mouth.

Shoreline Changes

20. A detailed investigation of shoreline changes at Sargent Beach between 1937 and 1973 was conducted by Seelig and Sorensen (1973a). Their report included a complete history of shoreline changes in the vicinity of Freeport Harbor and the BRDC delta. A 37-year net retreat of 730 ft was documented for Sargent Beach. This compares favorably with the 740-ft estimate of Mathewson and Minter (1976). Sediment supplied to the system by the Brazos River was estimated to be 1,800 million cu ft, of which 1,600 million cu ft was deposited asymmetrically on the BRDC delta and westward to the San Bernard River. The direction of net longshore transport for this area was determined to be to the west. This publication served as an excellent general reference, providing useful background information on the development of the BRDC delta.

21. Morton and Pieper (1975) conducted a study of shoreline changes in the vicinity of the Brazos River delta (San Luis Pass to Brown Cedar Cut) using aerial photographs and topographic maps. They found accretion rates on the BRDC delta (1930 through 1957) ranging from 27.4 to 256.6 ft per year.

Seelig and Sorensen (1973b) provide an account of "Historic Shoreline Changes in Texas" through the identification of changes in mean low water (mlw) at 226 points along the coast. Using the earliest and latest topographic surveys, they documented erosion seaward of the Freeport jetties, with accretion increasing steadily westward towards the BRDC. Their findings are consistent with shoreline change data presented by the US Army Engineer District, Galveston (in preparation). Nearshore changes following jetty construction at several Texas Gulf Coast inlets were examined by Morton (1977). He found that net bathymetric changes between 1857 and 1974 at Freeport Harbor were erosional and could be characterized by nearly equal volumes of updrift and downdrift erosion.

Texas Gulf Coast Inlets and Fluvial Systems

22. Inlet processes along the Texas coast were first examined by Price (1947, 1951, 1963). His studies identified the presence of a stable north-south orientation for channels occurring in many Texas tidal inlets. Herbich and Hales (1970) published a report on shoreline changes in the vicinity of San Luis Pass, as determined through the use of remote sensing techniques. Mason and Sorensen (1971) studied the physical and hydraulic properties, and the stability of Brown Cedar Cut. Results of their study suggested that the long-term stability of Brown Cedar Cut was enhanced by hurricanes and erosion of nearby beaches. In the absence of such forces, longshore drift caused channel shoaling and westward migration of the entire inlet system. A review of the history and present status of many of the Texas coastal inlets is presented by Schmeltz and Sorensen (1973). Mason (1981) describes the hydraulic characteristics and stability of five Texas inlet-bay systems, including the Brazos River/Freeport Harbor entrance. These reports serve as valuable sources of information regarding the characteristics of tidal inlets and fluvial systems on the Texas coast.

Wind and Wave Climate

23. Data for average wind and wave conditions were obtained from several sources. Wind speed and directional roses, based on hourly readings from 1905 to 1944, were published by the US Congress (1953). A step-resistance

wave gage was operated by CERC at the Galveston Pleasure Pier from March 1965 to July 1967. Data recorded by these gages were published by Thompson (1977). Bretschneider and Gaul (1956) hindcasted the wave climate from synoptic weather charts for the years 1950, 1952, and 1954 for an area offshore of Caplan, Texas, located east of Galveston. Wave hindcasts for selected hurricanes were predicted by Wilson (1957), and hurricane surge frequencies for the Gulf Coast of Texas were calculated by Bodine (1969).

PART IV: FIELD STUDIES

24. Results from the literature search indicate a paucity of field data from the BRDC and associated offshore region. This is true primarily because the BRDC was designed to absorb the fluvial sediment load and not to be a navigation project. Because results from the present study are dependent on accurate field data, several visits were made to the study area to collect the necessary field data.

Hydraulic Measurements, August 1984

25. The first field data were collected by the WES Hydraulics Laboratory (HL) or (WESHL) and SWG personnel during the period 25-26 August 1984. This field effort was designed to document the hydraulic and sediment-load discharge characteristics of the BRDC so that channel shoaling and advance maintenance volumes could be estimated.

26. Continuous recordings of tidal elevation were taken at two locations for the duration of the data collection period (Figure 8). Data were recorded with strip-chart recorders located at the Brazos River East Floodgate and at the crossing of HWY 36 approximately 4.5 miles upstream from the mouth. The water surface elevations at both stations are shown in Figure 9. The Gulf tidal range during the data collection effort was approximately 2.3 ft.

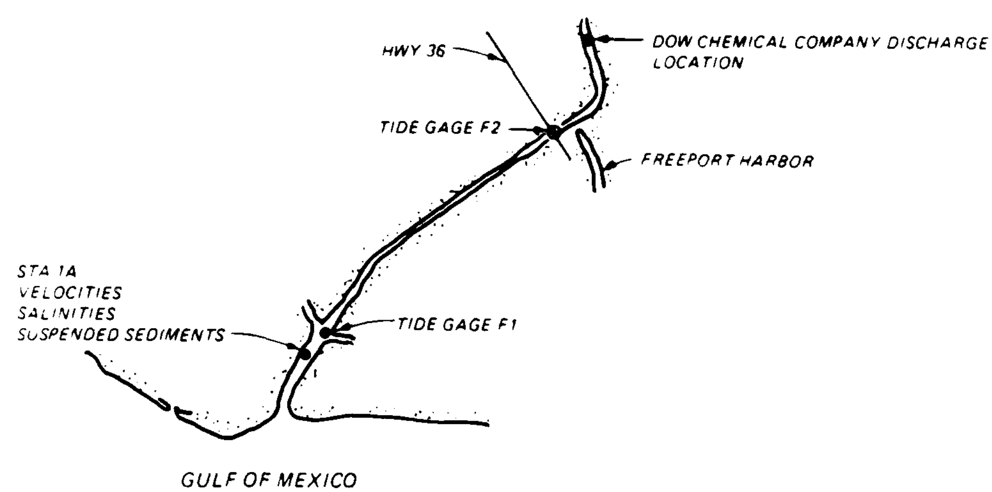


Figure 8. Location of WESHL survey measurement stations, August 1984

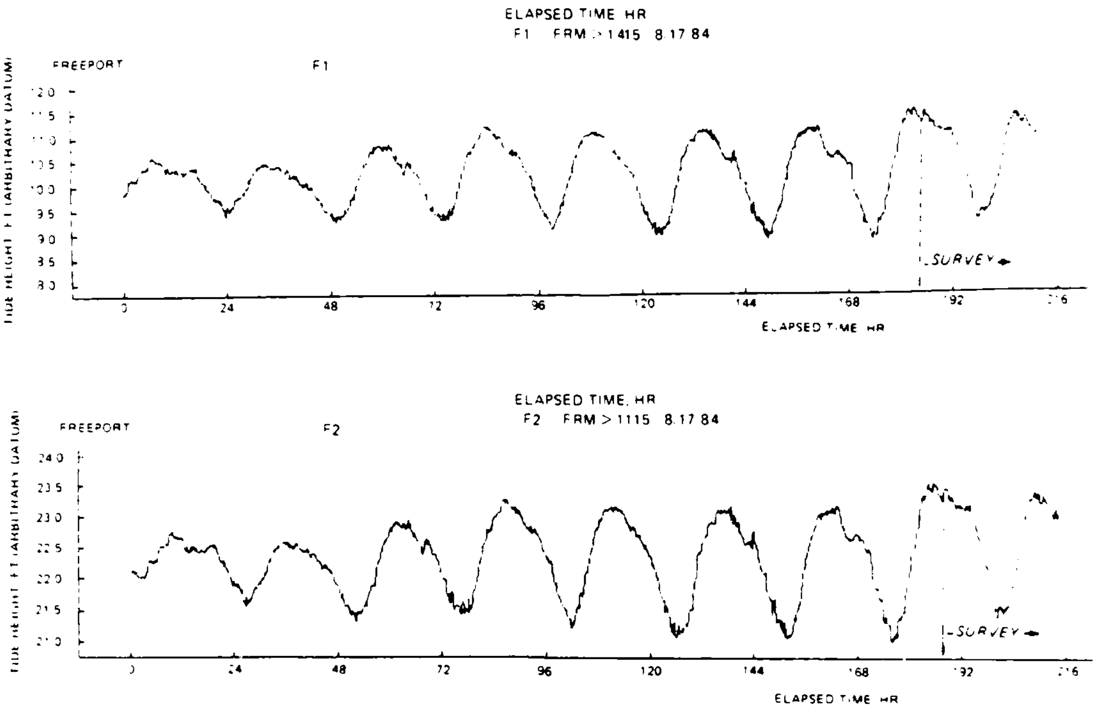


Figure 9. Water surface elevations recorded at sta F1 and F2

27. Current velocity, salinity, and suspended sediment measurements were taken during one complete tidal cycle at a midriver location 0.5 mile downstream from the GIWW crossing (Figure 8, sta 1A). These data were collected simultaneously at the surface, middepth, and bottom of the water column. The results of these measurements are presented in Figures 10, 11, and 12. Current measurements at sta 1A showed the existence of a partially stratified flow with the surface flow predominantly in the ebb direction and the bottom flow predominantly in the flood direction (Figure 10). This stratified flow was evidenced by the surface current which predominantly flowed in the ebb direction, while the bottom current predominantly flowed in the flood direction (Figure 10). Salinity varied from 26 to 33 ppt at the surface to 29 to 33 ppt at the bottom (Figure 11). Suspended sediment concentrations at sta 1A ranged from 6 to 38 ppm at the surface to 10 to 68 ppm at the bottom (Figure 12). The river discharge was approximately 800 cu ft/sec during the survey. The Dow Chemical Company discharged an additional 4,000 cu ft/sec of seawater at the location shown in Figure 8 for a total discharge of approximately 4,800 cu ft/sec. The density flow seems stronger than that which would be created by a 3- or 4-ppt vertical salinity differential. The injection of seawater at the Dow Chemical outfall, possibly at a different temperature than

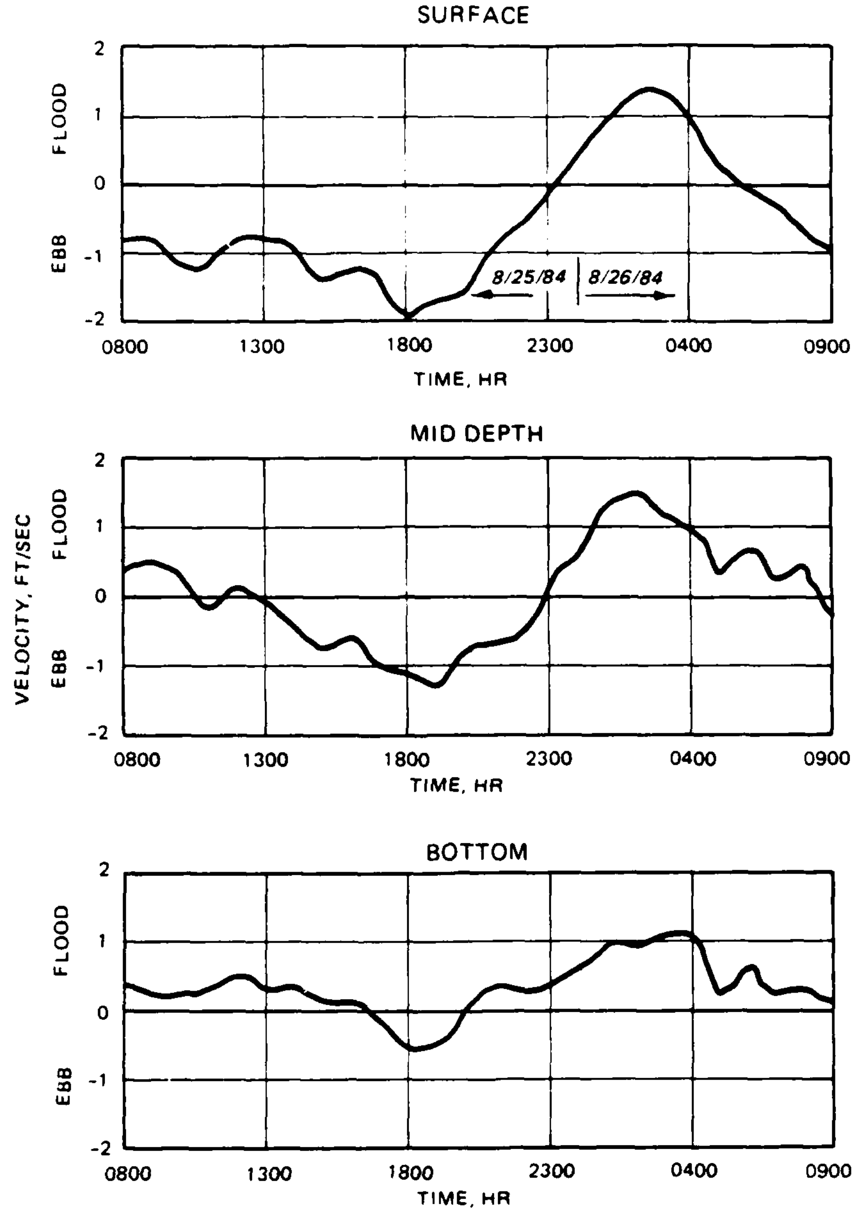


Figure 10. Current velocity measurements at sta 1A

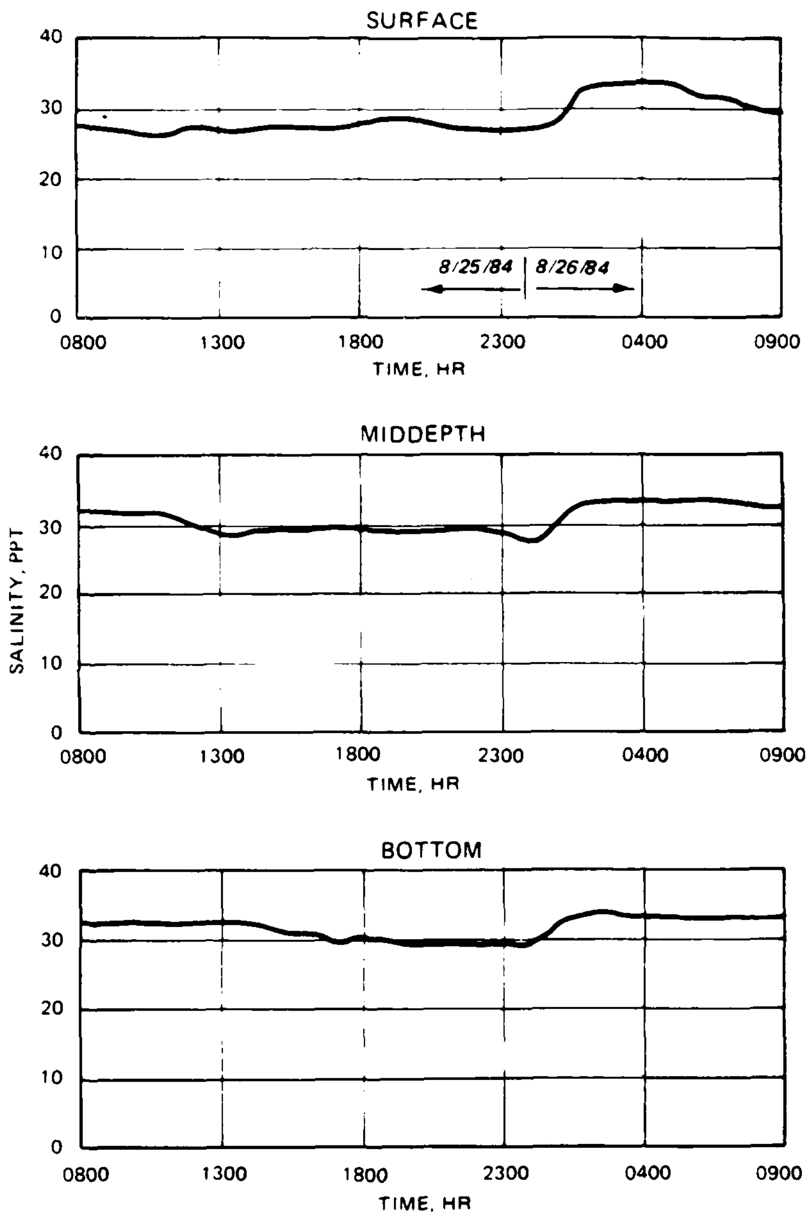


Figure 11. Salinity measurements at sta 1A

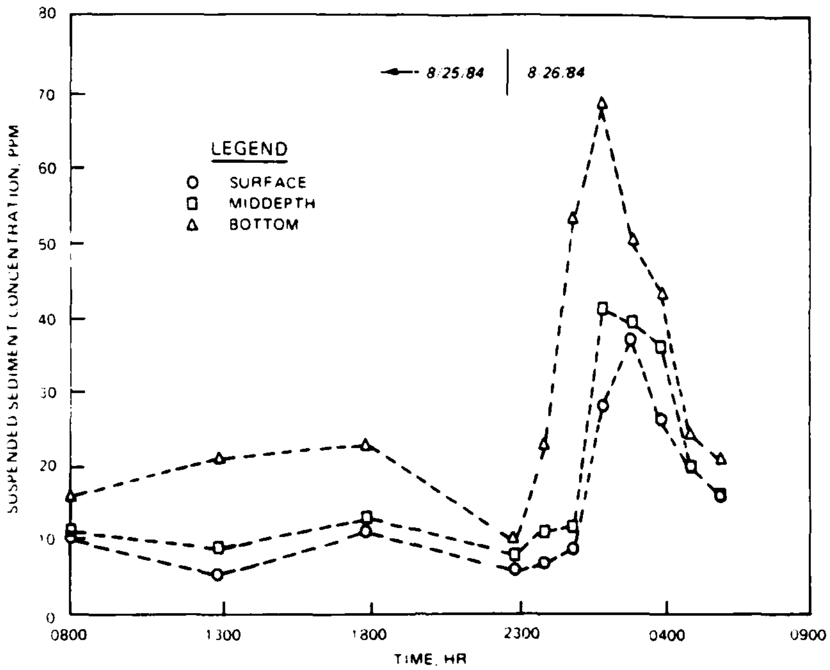


Figure 12. Suspended sediment concentrations at sta 1A

the receiving water, may account for the stratified flow structure in the entrance channel.

Hydraulic Measurements, November 1958

28. Grozier and Yost (1959) discuss an extensive field study conducted by the USGS in the BRDC on 12-13 November 1958. The field effort consisted of water surface elevation, current, and salinity measurements obtained at the location shown in Figure 13. The results of these measurements are shown in Figures 14, 15, and 16, respectively. The river flow was approximately 1,900 cu ft/sec with Dow Chemical Company pumping approximately 2,230 cu ft/sec of salt water from Freeport Harbor into the Brazos River at the location shown in Figure 13. The Gulf tidal range during the study was about 2.3 ft (Figure 14). Current measurements indicated a partially stratified system, with maximum ebb velocities occurring in the upper water column and maximum flood velocities occurring in the lower water column (Figure 15). During the survey surface salinities varied from 11 to 17 ppt, while bottom salinities varied from 23 to 28 ppt, indicating a higher degree of stratification than during the August 1984 survey (Figure 16). The report concluded that stratification along the BRDC was enhanced significantly by the Dow Chemical Company discharge.

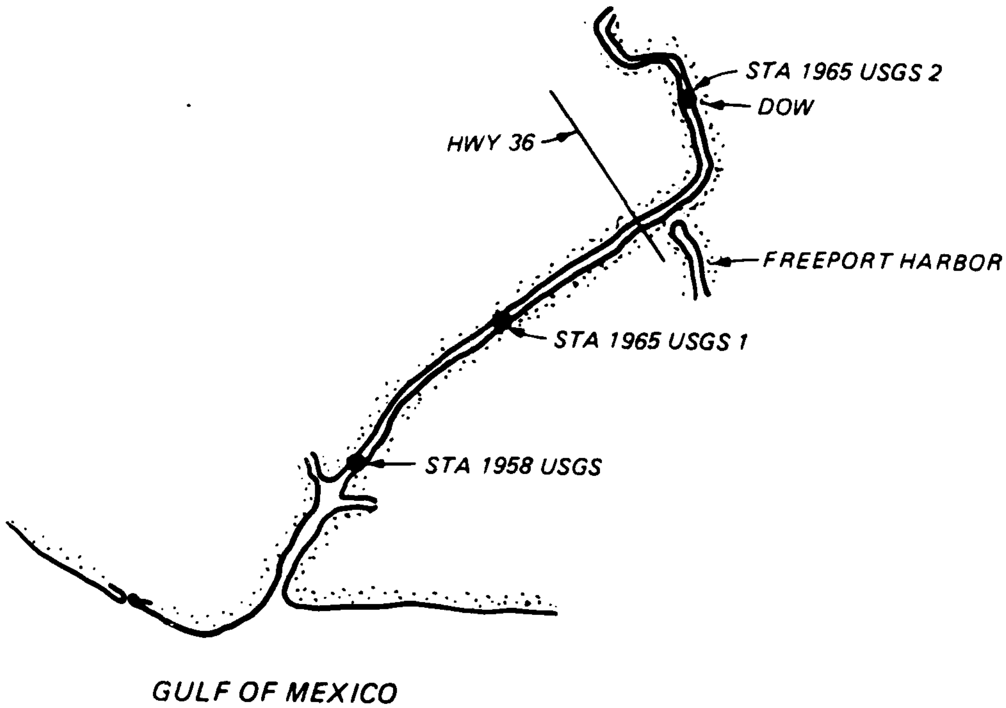


Figure 13. Location of USGS survey measurement stations, November 1958 and March 1965

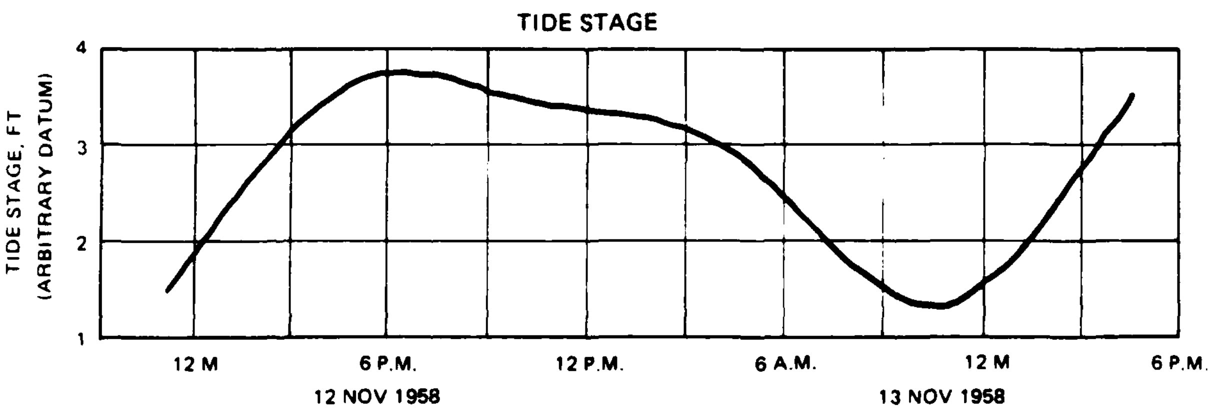


Figure 14. Water surface elevation at USGS 1958 station

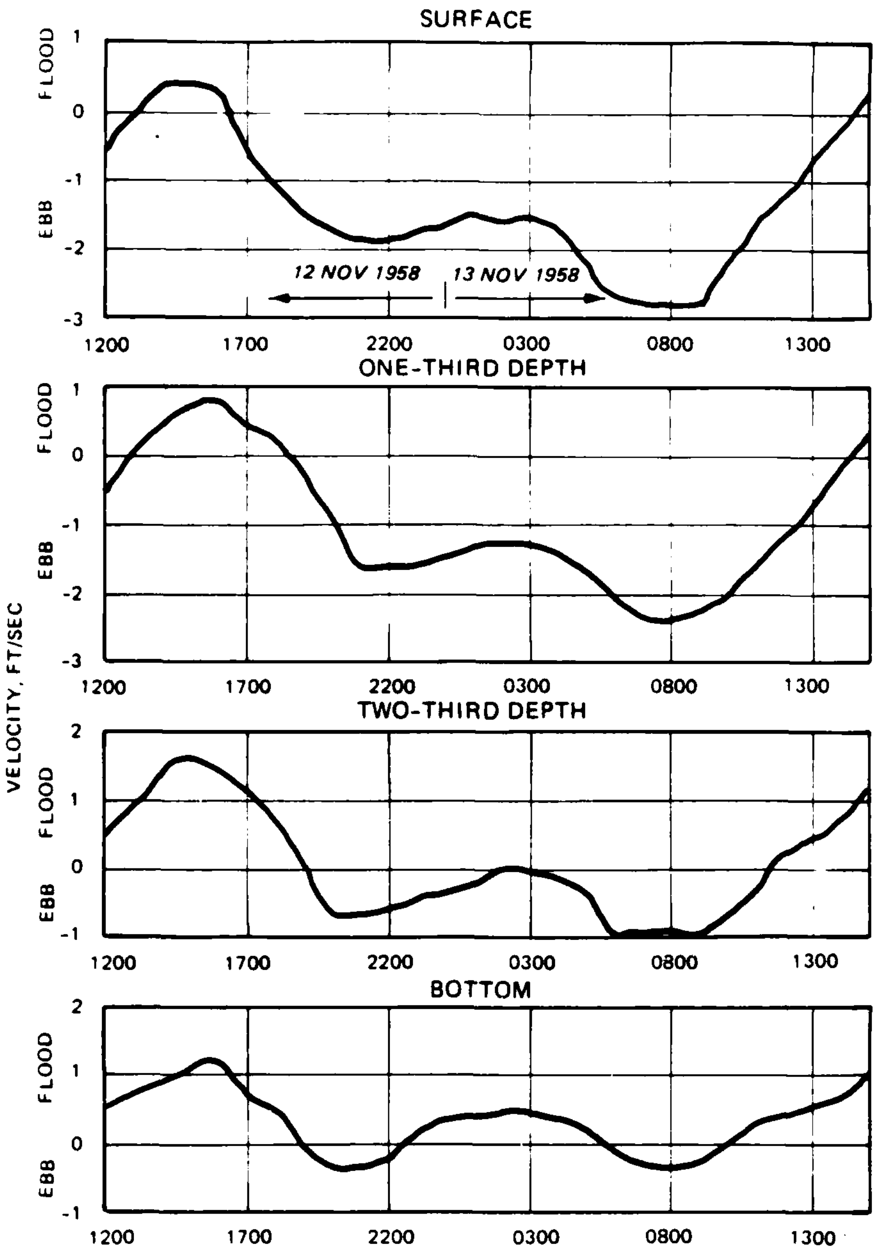


Figure 15. Current velocity measurements at USGS 1958 station

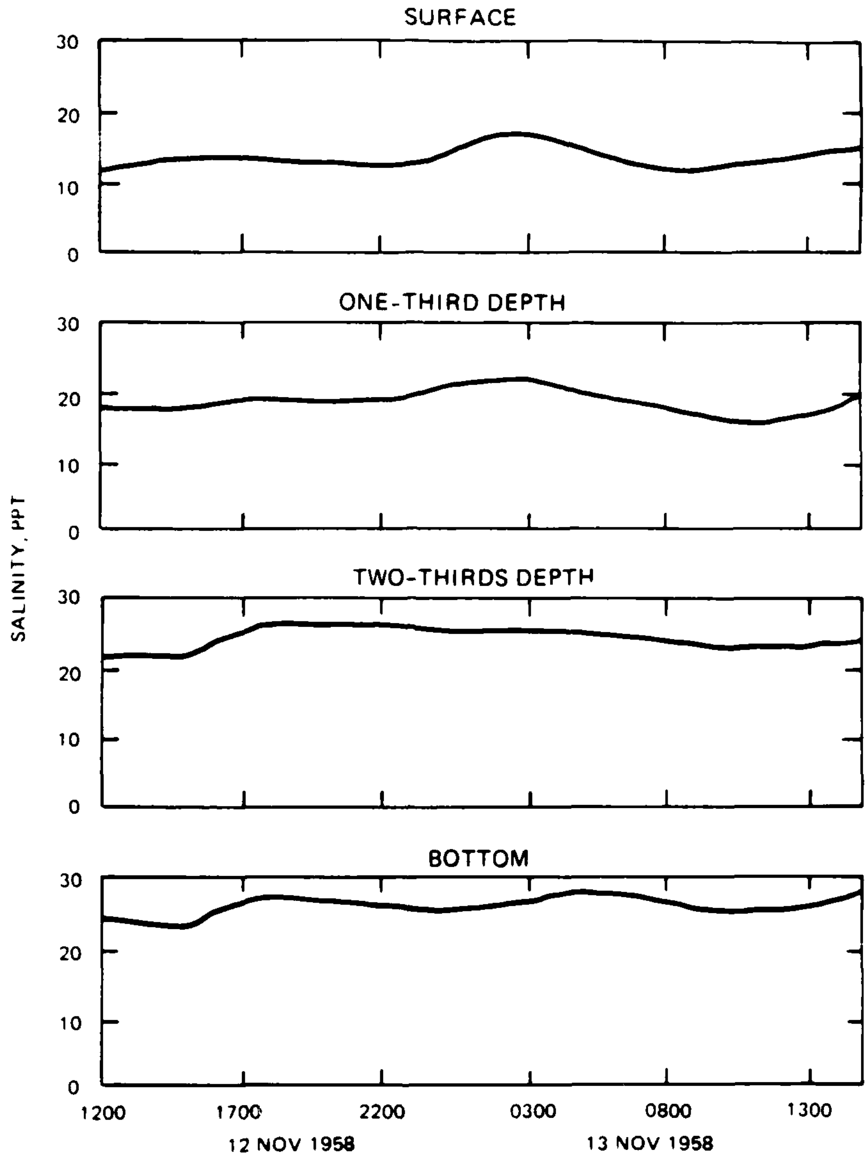


Figure 16. Salinity measurements at USGS 1958 station

Hydraulic Measurements, March 1965

29. Johnson, Rawson, and Smith (1967) describe a survey conducted by the USGS in the BRDC during the period 29-30 March 1965. The field study consisted of water surface elevation, current, and salinity measurements, obtained at the locations shown in Figure 13. The results of these measurements are shown in Figures 17, 18, and 19. The river flow was approximately 2,000 cu ft/sec with Dow Chemical Company pumping 3,950 cu ft/sec of salt water from Freeport Harbor into the Brazos River at the location shown in

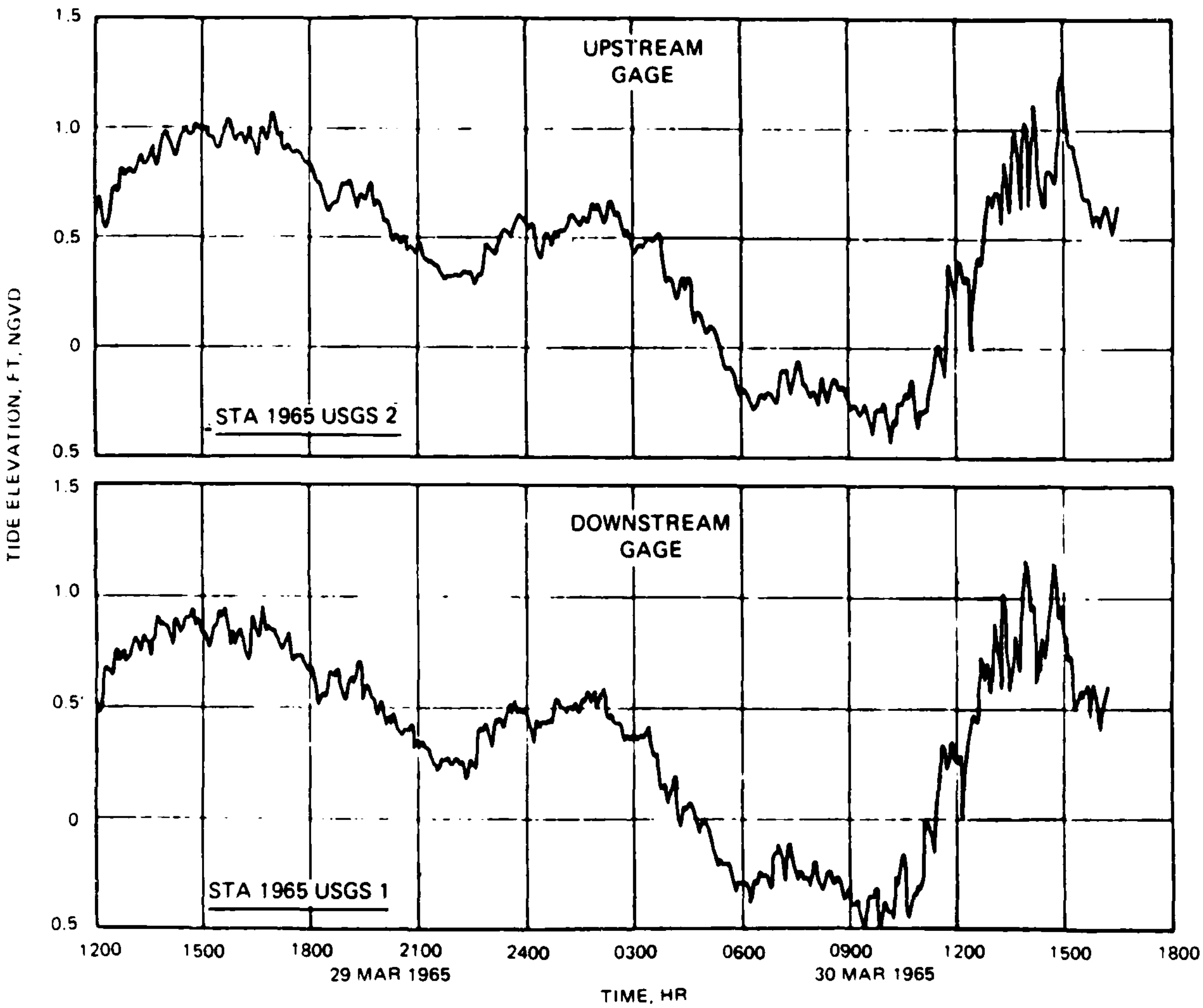


Figure 17. Water surface elevations at USGS 1965 sta 1 and 2

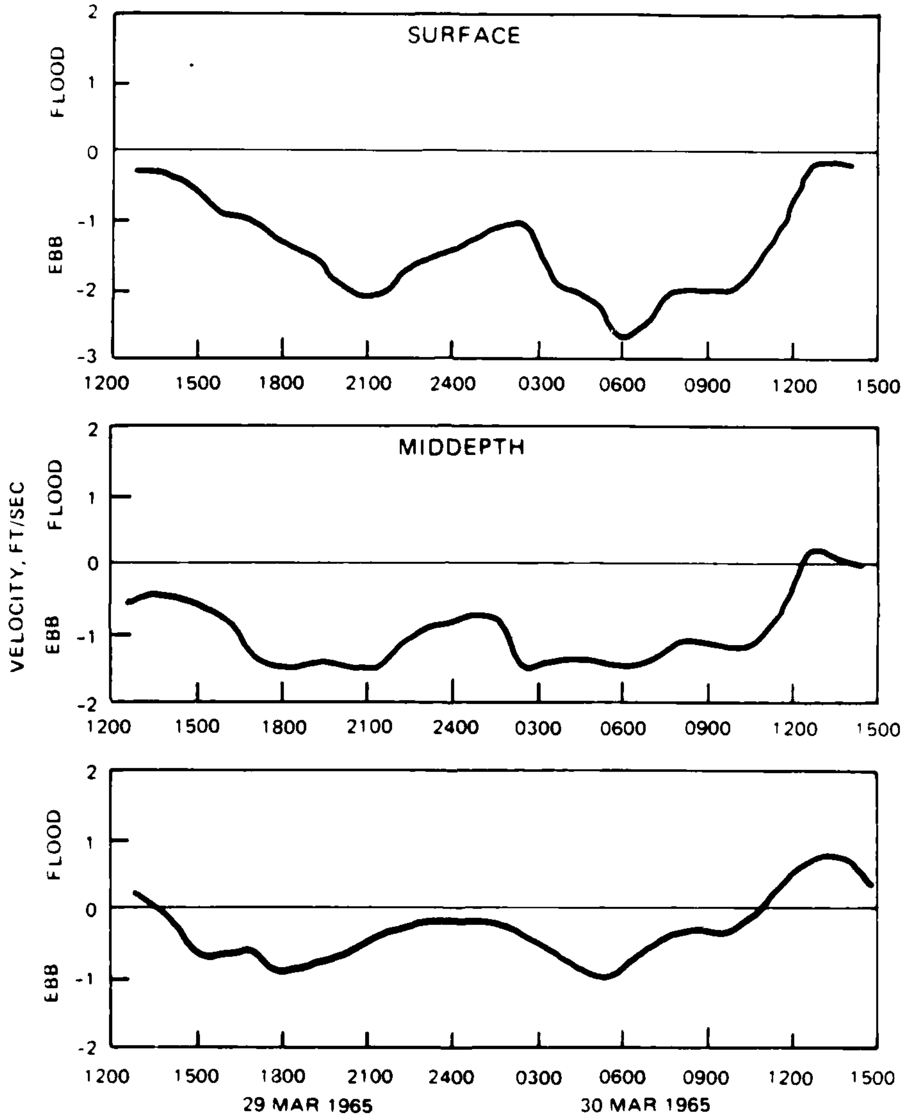


Figure 18. Current velocity measurements at USGS 1965 sta 1

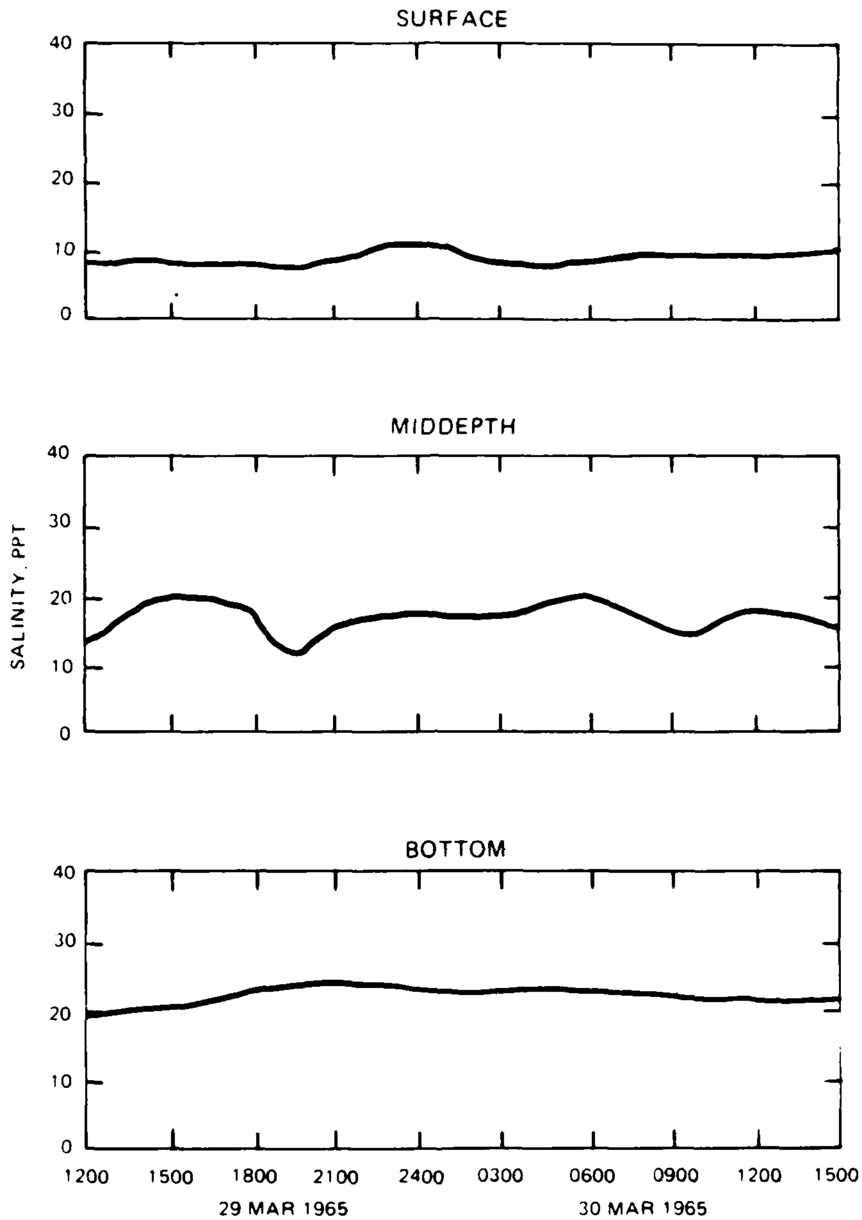
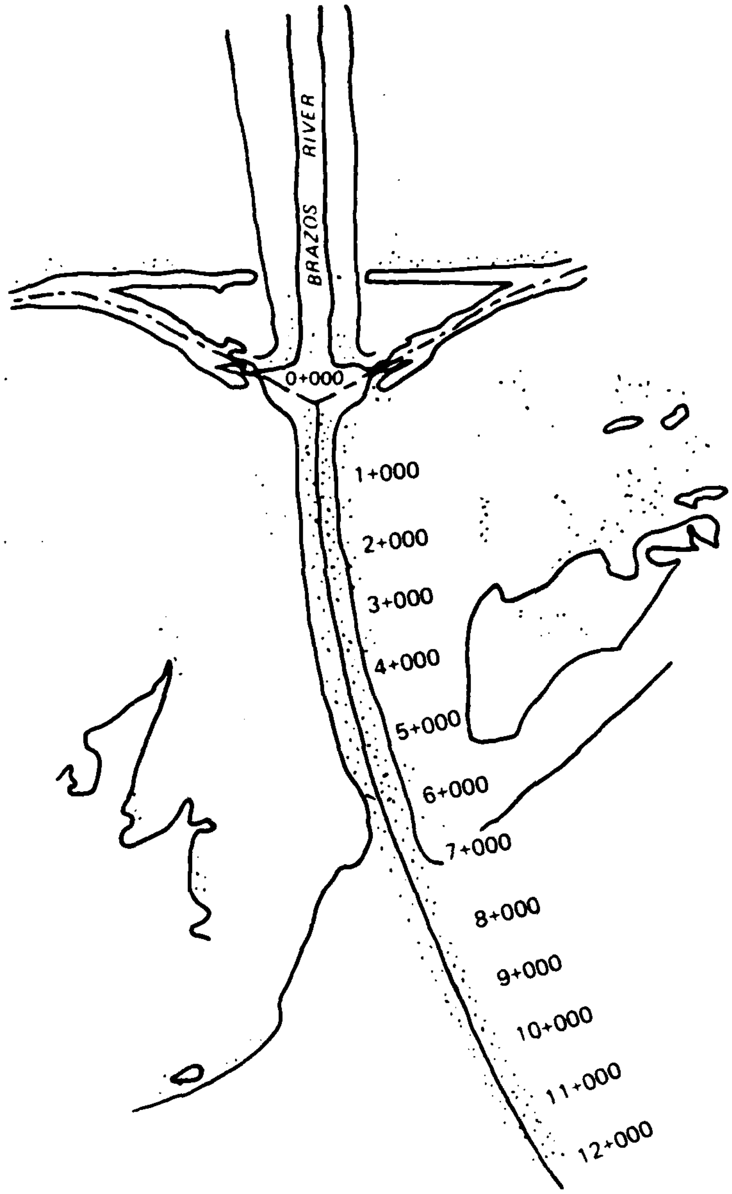


Figure 19. Salinity measurements at USGS 1965 sta 1

Figure 13. The Gulf tidal range was approximately 1.4 ft during the survey (Figure 17). Current measurements indicated almost total ebb dominant flow, with only a short period of flood flow in the lower water column (Figure 18). Even though the currents were predominantly ebb directed during the survey, salinities ranged from 8 to 11 ppt at the surface to 20 to 24 ppt at the bottom, thus demonstrating the effects of Dow's Chemical Company seawater discharge on the lower river salinity regime (Figure 19).

Bathymetric Surveys of the BRDC

30. On 6 August 1982, SWG surveyed a longitudinal profile along the thalwag of the BRDC from sta 0+00 to sta 155+00 (Figure 20). The controlling channel depth was -3.0 ft (mlt) on the entrance bar (ebb-tidal delta).



BOTTOM SURVEY TAKEN
6 AUG 1982

STATION	DEPTH, FT MEAN LOW TIDE
0+000	-12.0 FT
0+500	-10.9
1+000	-11.0
1+500	-10.5
2+000	-9.9
2+500	-9.8
3+000	-9.3
3+500	-9.0
4+000	-7.0
5+000	-6.5
5+500	-5.0
6+000	-4.0
6+500	-4.5
7+000	-3.0
7+500	-3.5
8+000	-5.0
8+500	-7.0
9+000	-9.0
9+500	-11.0
10+000	-13.0
10+500	-15.0
11+000	-16.0
11+500	-17.0
11+700	-18.0
12+400	-19.0
13+000	-20.0
15+500	-21.0

SCALE
1000 0 1000 2000 FT

Figure 20. Longitudinal survey of BRDC, August 1982

31. On 12-13 December 1984, SWG measured five channel cross sections between the mouth of the BRDC and a location 2 miles upstream (Figure 21). The five cross sections are shown in Figure 22.

32. These two surveys represent two extremes in diversion channel geometry, the August 1982 survey showed a shoaled or choked condition while the December 1984 survey showed an eroded condition in which previously deposited sediment had been transported out of the diversion channel. During times of the year when the riverine sediment loading exceeds the transport capacity, sediment is deposited along the diversion channel. During times of the year when riverine sediment loading is less than the transport capacity, material is scoured from the channel. The volume of material required to infill from the eroded condition to the shoaled condition is about 333,000 cu yd, as represented in Figure 23.

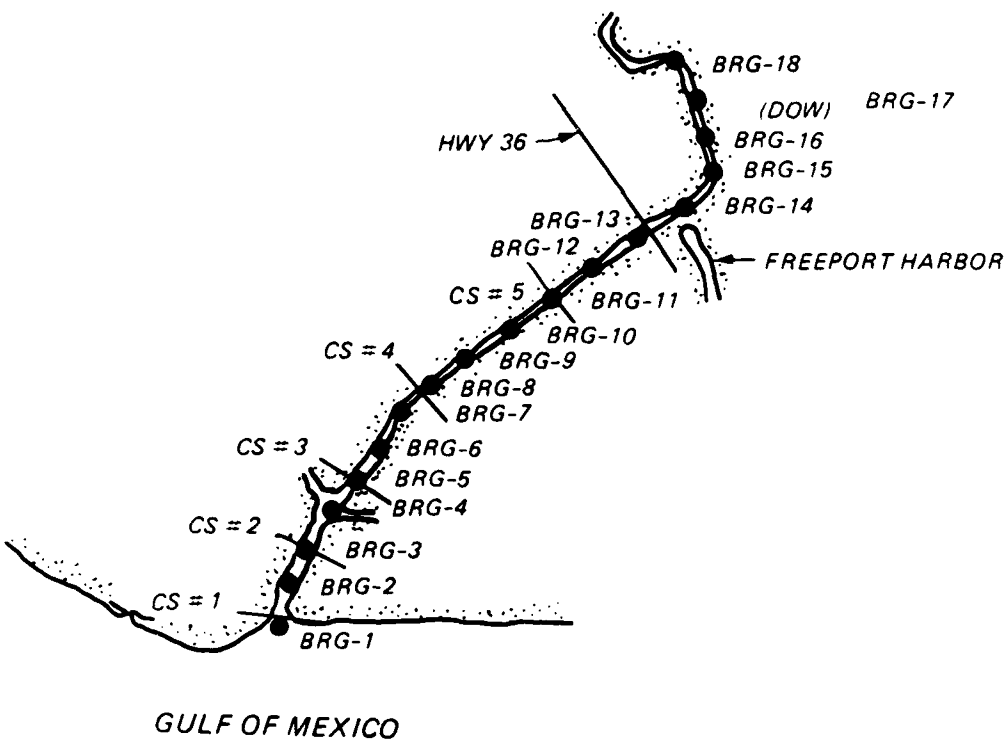


Figure 21. Location of survey cross sections (December 1984) and bed samples (February 1985) collected along lower BRDC

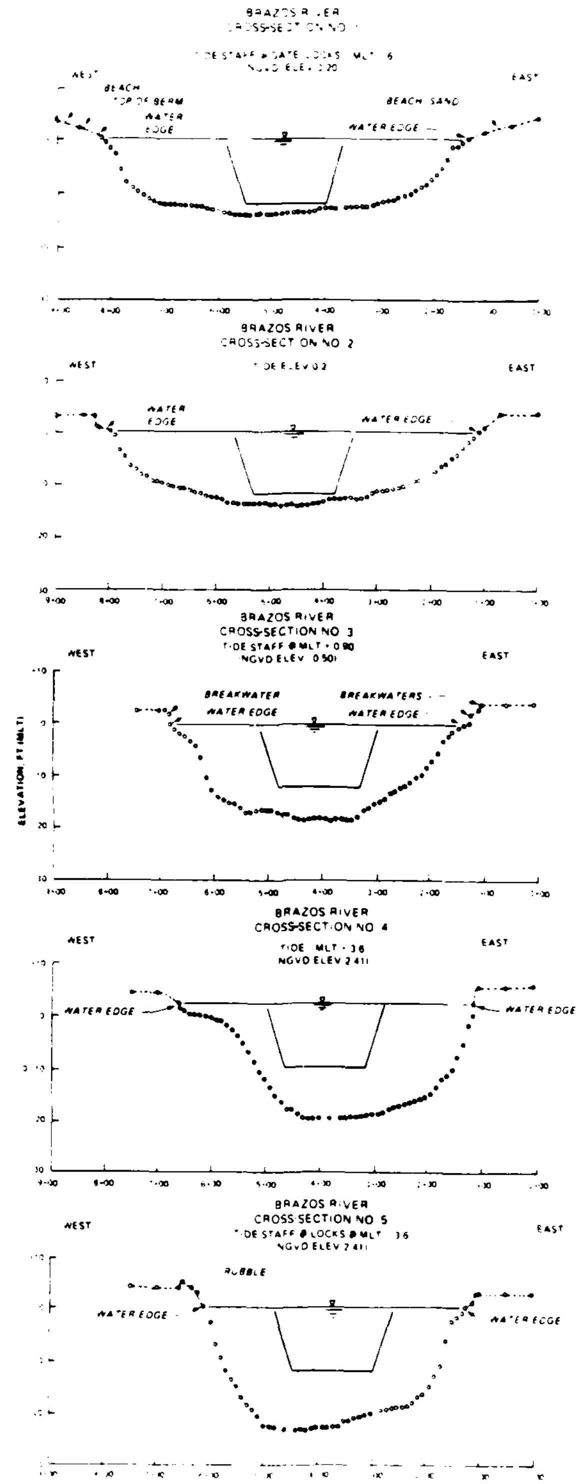


Figure 22. Channel cross sections of lower BRDC

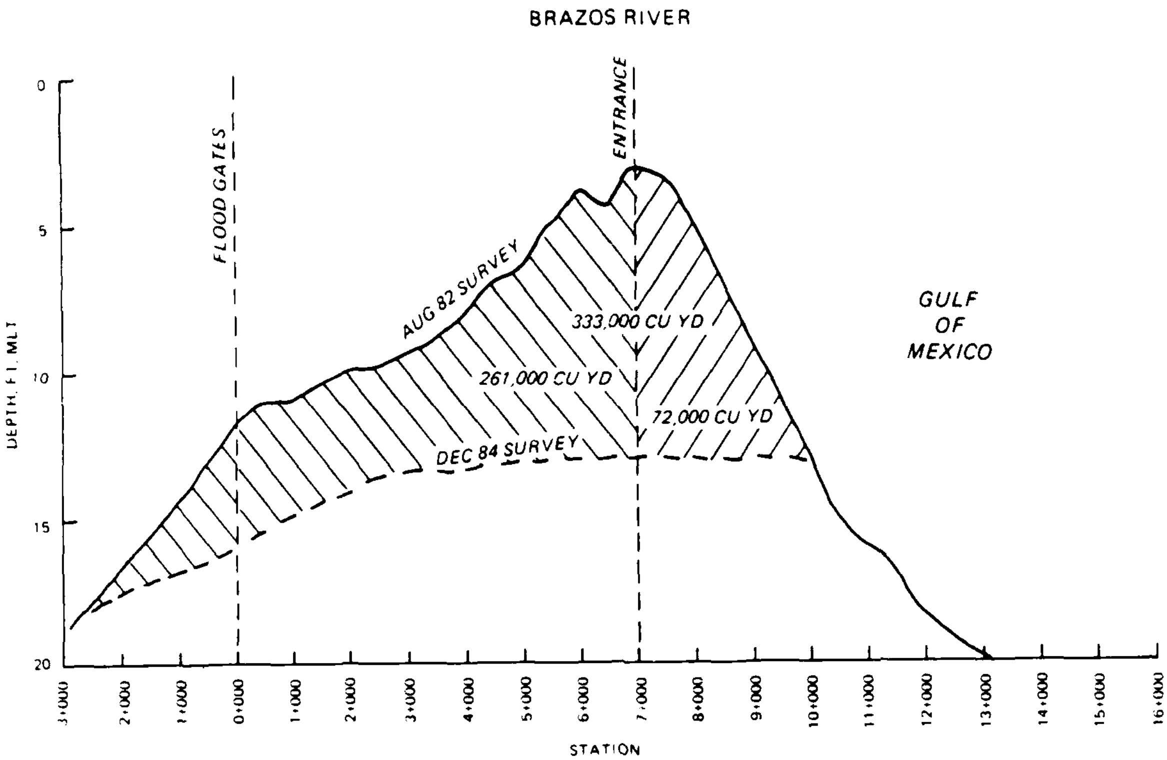


Figure 23. Depth comparison of August 1982 and December 1984 lower BRDC surveys

Hydrographic and Sediment Analysis, Brazos River Delta

33. A second field effort was conducted jointly by CERC and SWG personnel on 6-8 February 1985 to obtain a detailed bathymetric survey and to collect sediment samples from the BRDC and adjacent offshore region. Prior to these efforts, the most recent detailed bathymetric data published for this area were obtained in 1937 and are published in NOS nautical chart No. 11321. The most up-to-date analysis of surficial sediments was that conducted by Nienaber (1963).

Bathymetry

34. The bathymetric survey was conducted using a Corps of Engineers survey boat equipped with a mini-ranger location system. Fifteen shore-normal profiles were taken from an onshore depth of 10 ft to an offshore depth of 30 ft National Geodetic Vertical Datum (NGVD). The profiles were spaced at 0.5-mile intervals from approximately 3.5 miles west of the Freeport jetties to the mouth of the San Bernard River (Figure 24). The offshore limits of the

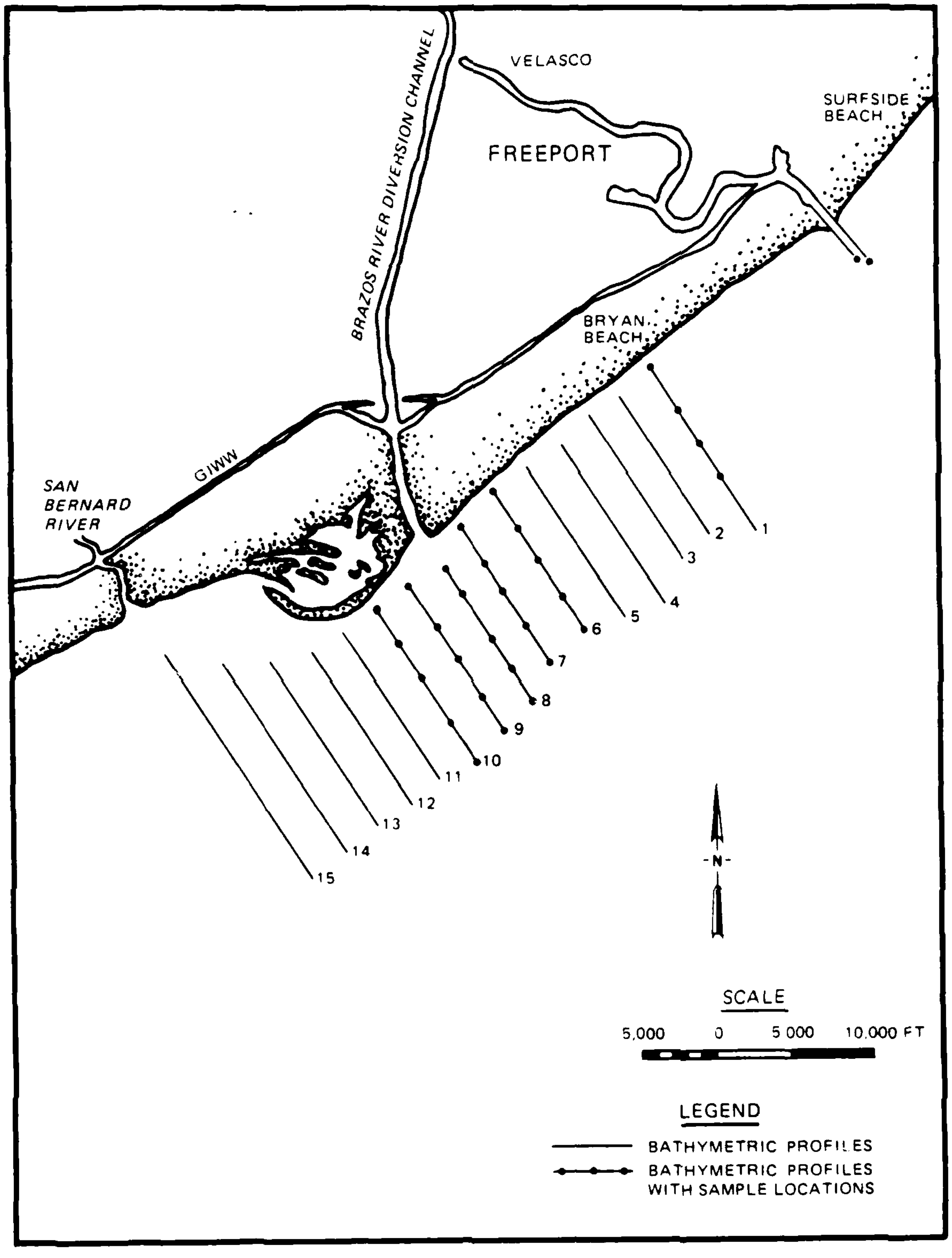


Figure 24. Location of bathymetric survey profiles and sediment samples collected on the BRDC delta, February 1985

survey were chosen to cover the suspected seaward limit of the delta. This location was estimated from NOS nautical chart No. 11321 which indicates that the contours become roughly parallel at this depth.

35. The water depth and location were recorded every 660 ft along each profile. These data were reduced to mlw and printed at a scale of 1:20,000. A contour map prepared from the 1985 data is shown in Figure 25. The Brazos River delta clearly has a dominating effect on the bathymetry of this area, resulting in a deflection of the 30-ft depth contour. The shape of the delta is roughly symmetrical, although it is offset southwest of the center line of the BRDC. Seelig and Sorensen (1973a, p 140) indicate that the delta had a similar size and morphology in 1973. A larger scale map of the area including water depths of 100 ft was published by Nienaber (1963). His data show that the delta extends seaward to deflect the 50-ft depth contour, while maintaining a symmetrical configuration.

Sediments

36. Surface grab samples were collected on five of the survey profiles at 0.5-mile spacing beginning at the 30-ft depth contour working landward. A total of 29 samples were taken in the offshore region. The locations where each of the samples were taken are shown in Figure 24. Grab samples were also collected along the BRDC thalwag, from the mouth to a distance approximately 6.5 miles upstream. A total of 18 samples were taken from the BRDC (analysis completed on 9 of the samples); their locations are illustrated in Figure 21.

37. A split of each sample was used to determine the grain-size distribution. The subsamples were wet sieved through US Standard sieve No. 200 (0.0744 mm) to separate very fine sand from coarse silt. A standard dry sieve analysis was performed on those samples containing greater than 50 percent sand, while silt and clay fractions were given as a percent of the total. A standard hydrometer analysis was performed on the samples containing greater than 50 percent silt and clay, and the remaining sand fraction was given as a percent of the total. The results were plotted as cumulative frequency curves and are presented in Appendix A. Summaries of the grain-size distributions are included in Tables 1 and 2.

38. The variation in grain-size on the delta was small with the finest size measured as clay (<0.001 mm) and the coarsest as fine sand (0.13 mm) (Figure 26). The largest grain sizes were found in samples collected along the eastern edge of the survey area (samples I-1 through I-4), and from the

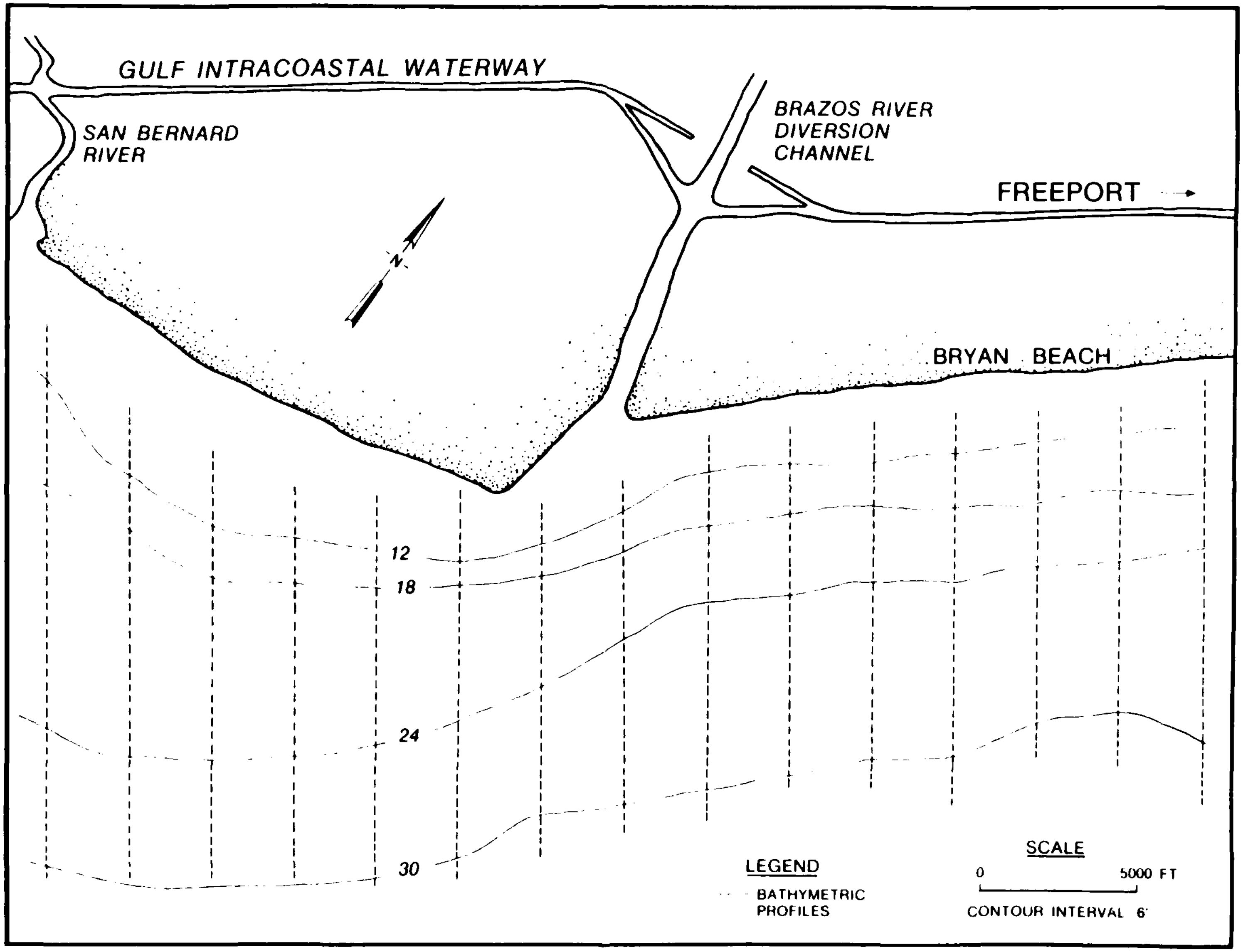


Figure 25. BRDC delta bathymetry, February 1985

Table 1

Brazos River Delta Sediment Analysis, Graphical Median, mm

Sample No.	50% Finer than by Weight, mm	Wentworth Size Class
I-1	0.08	Very fine sand
I-2	0.11	Very fine sand
I-3	0.12	Very fine sand
I-4	0.10	Very fine sand
VI-1	0.09	Very fine sand
VI-2	Bulk of sample not analyzed (≤0.08)	
VI-3	<0.001	Clay
VI-4	<0.001	Clay
VI-5	0.001	Clay
VII-1	0.13	Fine sand
VII-2	0.08	Very fine sand
VII-3	0.003	Fine silt
VII-4	0.002	Fine silt
VII-5	0.003	Fine silt
VIII-1	Bulk of sample not analyzed (≤0.08)	
VIII-2	0.002	Fine silt
VIII-3	0.001	Clay
VIII-4	<0.001	Clay
VIII-5	0.004	Fine silt
IX-1	0.12	Very fine sand
IX-2	0.003	Fine silt
IX-3	0.01	Fine silt
IX-4	<0.001	Clay
IX-5	<0.001	Clay
X-1	0.001	Clay
X-2	0.02	Coarse silt
X-3	0.004	Fine silt
X-4	0.004	Fine silt
X-5	0.002	Clay

Table 2

Brazos River Diversion Channel Sediment Analysis, Graphical Median, mm

Sample No.	50% Finer than by Weight, mm	Wentworth Size Class
BRG-1	0.17	Fine sand
BRG-3	<0.001	Clay
BRG-5	<0.001	Clay
BRG-7	<0.001	Clay
BRG-9	<0.001	Clay
BRG-11	<0.001	Clay
BRG-13	<0.001	Clay
BRG-15	0.003	Fine silt
BRG-17	<0.001	Clay

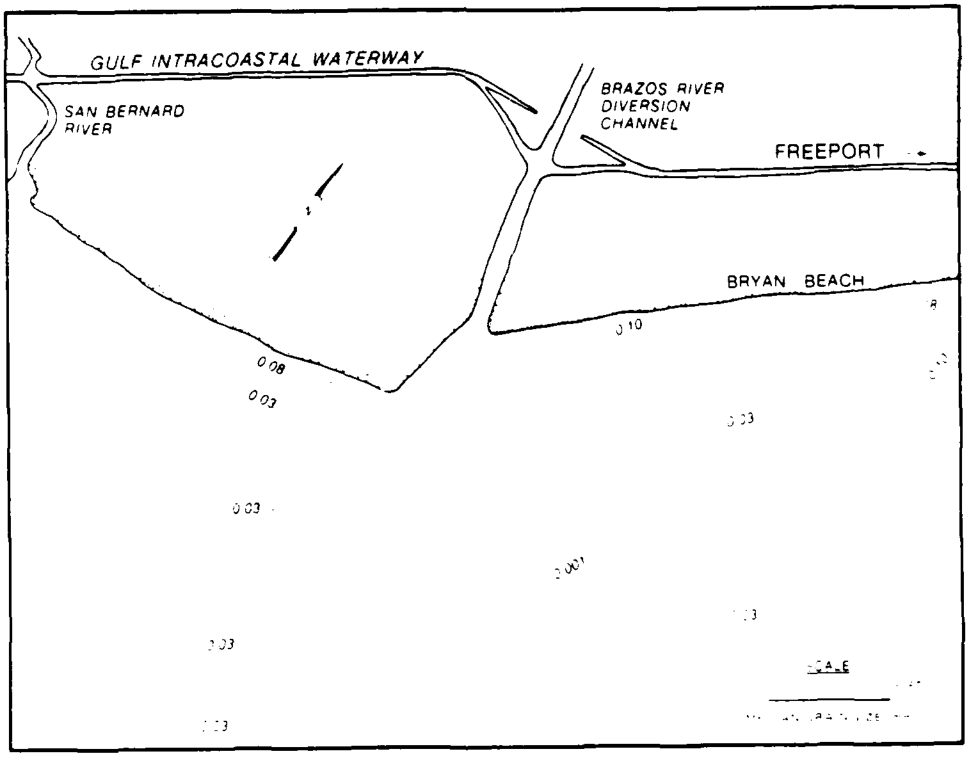


Figure 26. Contour plot of 1985 BRDC delta median grain size

nearshore samples taken at 10-ft water depths (samples VI-1, VII-1, VIII-11, IX-1; Figure 26). A decrease in median grain size occurred in the offshore direction along each of the traverses, excluding the westernmost one, which showed clay- and silt-sized particles in the nearshore region. The contour plot of median grain-size (Figure 26) indicates the presence of an elongate deposit of clays located on the updrift side of the delta. Almost exclusively, the grain-sizes within the BRDC were classified as clay and silt. The only exception occurred at the mouth of the river where fine sand (0.17 mm) was found.

39. The median grain-size distribution found in this study (Figure 26) compares favorably with the mean grain-size distribution reported by Nienabar (1963) (Figure 27). Both studies identify a sequence of seaward fining sediments composed of very fine sands, silts, and clays. Mathewson and Minter (1976) found that bedload samples collected near the mouth of the BRDC contained approximately 50 percent fine sand (0.20 mm). These sediments are only slightly coarser than the 0.17-mm grab samples collected at the BRDC mouth during this study (Table 2).

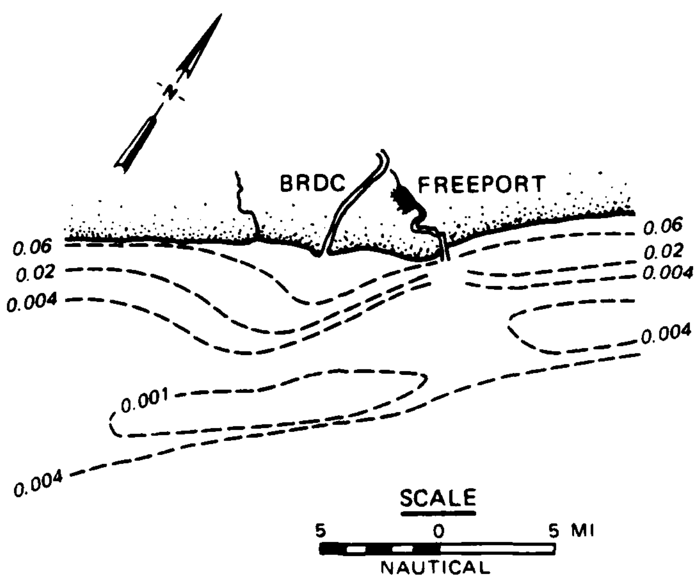


Figure 27. Contour plot of 1955 BRDC delta mean grain size (modified from Nienaber 1963)

PART V: ANALYTICAL AND NUMERICAL STUDIES

40. The following studies were conducted by WES's Coastal Engineering Research Center (CERC) and Hydraulics Laboratory (HL).

41. Components of the study conducted by CERC included:

a. An evaluation of shoreline changes recorded in aerial photographs and charts.

b. Determination of nearshore transport quantities and rates using LEO data.

c. A wave-refraction analysis using a numerical refraction/diffraction model.

d. Determination of channel shoaling rates at the mouth of the Brazos River utilizing results from each of the above studies.

42. Components of the study conducted by HL included:

a. Determination of riverine sediment loading.

b. Determination of diversion channel shoaling rates for the various channel depths proposed.

Historical Shoreline Changes

43. Shoreline changes in the vicinity of the BRDC delta have been analyzed by Odem (1953), Nienaber (1963), Seelig and Sorensen (1973a), and Morton and Pieper (1975). Data for this study were compiled from numerous sources, including NOS and Corps surveys, and Federal and private aerial photograph companies.

44. The major shoreline change events associated with development of the BRDC delta are summarized below. Reference is given to Seelig and Sorensen (1973a) for more detailed information. A listing of the source for each of the shoreline changes discussed in this report is included in Table B1.

1852-1855

45. The first detailed topographic surveys of the study area were published by NOS. The surveys show that the shoreline was essentially straight, with a small, partially subaerial delta to the west of the Brazos River (Figures 28-29).

1887-1932

46. Construction of the Freeport jetties between 1881 and 1896 caused a significant enlargement of the Brazos River delta, and accretion of the

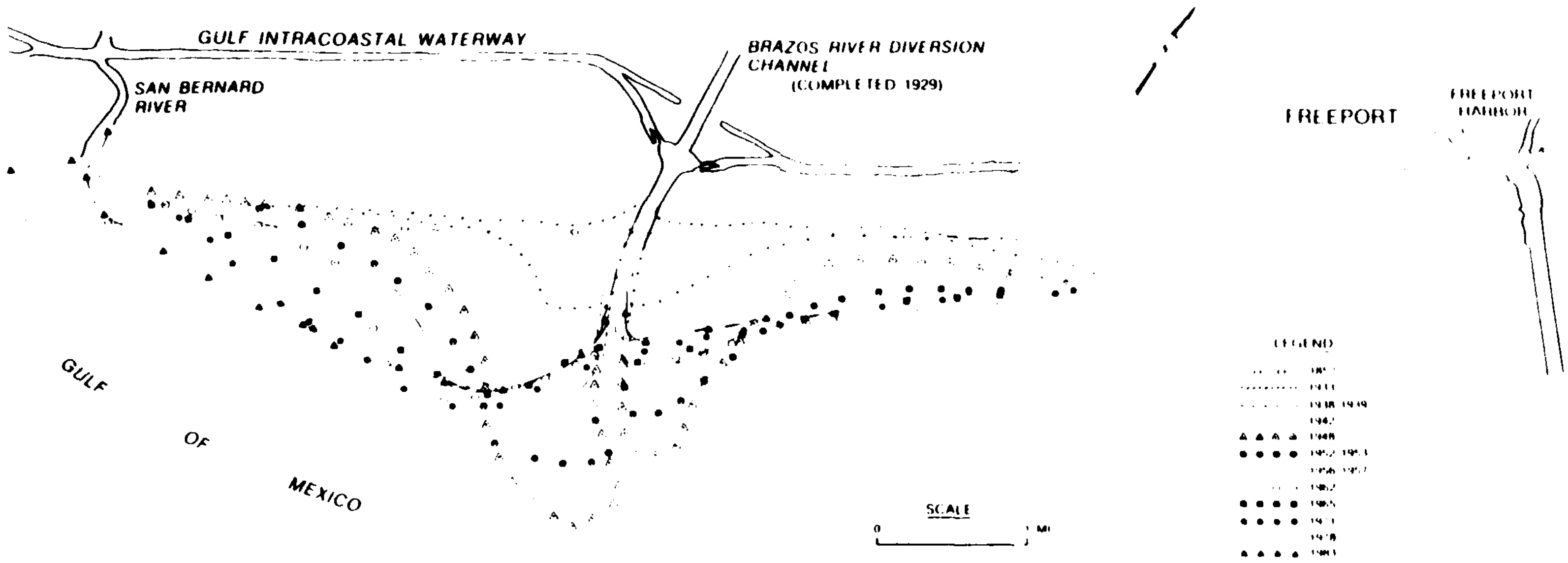


Figure 28. Shoreline change map for BRDC delta, 1852-1983 (modified from Seelig and Sorensen 1973)

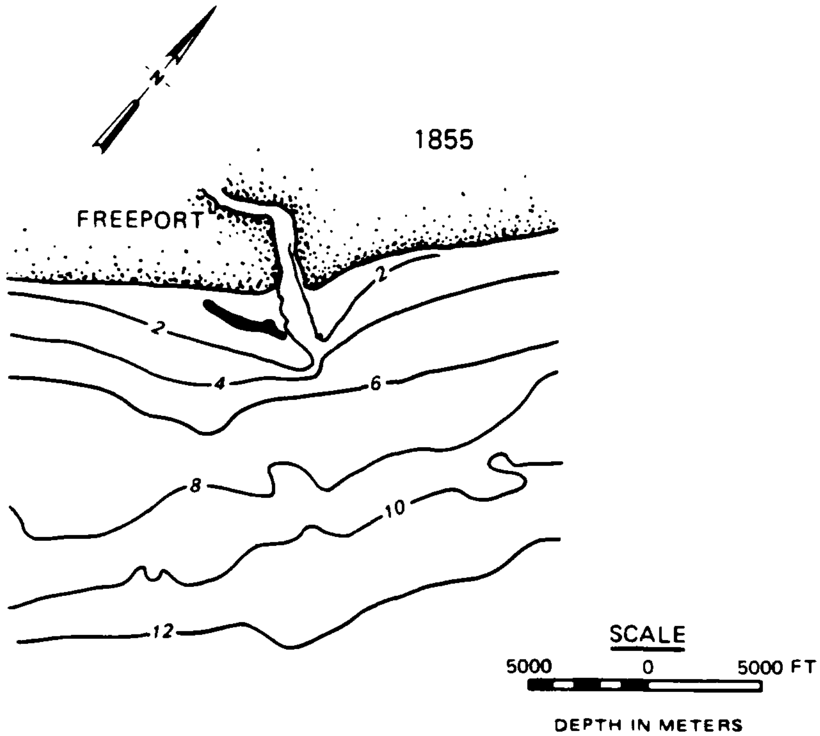


Figure 29. Bathymetric survey of Freeport Harbor, 1855

adjacent shorelines. The jetties appear to have concentrated the Brazos River sediments seaward of the littoral zone, causing deposition of the delta downdrift of the jetties. At the same time, the jetties interrupted the longshore drift and provided a sheltered area for accretion of the adjacent beaches. Accounts by Odem (1953) show that between 1887 and 1932 the southwest shoreline advanced 4,000 ft seaward, and the northeast shoreline advanced 1,800 ft (Figure 30). By 1932, deposition at the mouth of the rerouted BRDC had built an extensive subaqueous delta (Odem 1953).

<u>1933</u>

47. During the four years following construction of the BRDC, the old delta at Freeport decreased in size. In 1933 the new delta exhibited rapid growth with subaerial deposition occurring on the southwest side of the new channel in 1933 (Figure 28). Growth of the old Brazos delta ceased as a result of the diversion of sediments from Freeport Harbor. Erosion of the old delta by net westerly longshore currents added to the sediments deposited on the new delta. Nienaber (1963) reports an extremely high river discharge and sediment load for the Brazos River in 1932, therefore accounting for the increased pulse of growth noted in 1933.

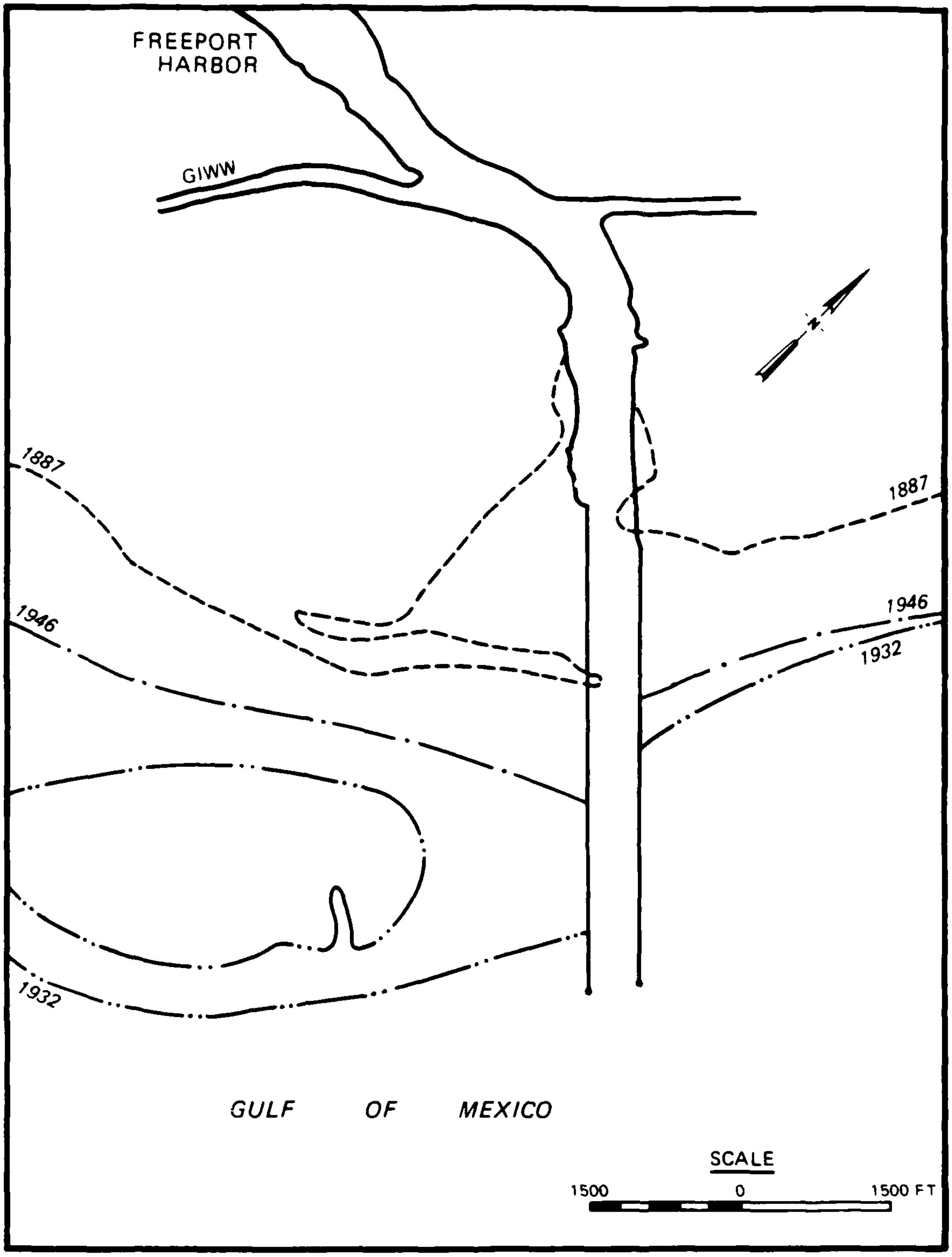


Figure 30. Shoreline change map for Freeport Harbor, 1887-1946

1946

48. The shoreline southwest of Freeport Harbor retreated 1,300 ft from its 1932 position, while relatively minor changes occurred on the northeast side of the jetties (Nienaber 1963, Figure 30). Nienaber (1963) attributes this to the absence of fluvial sediments in this area resulting from the construction of the BRDC. Growth of the BRDC delta remained relatively constant between 1933 and 1946.

1948

49. The Brazos River delta occupied its seaward-most position in 1948 (Figure 28). Seelig and Sorensen (1973a) indicate that the delta advanced 8,000 ft seaward between 1946 and 1948. There is little direct evidence indicating why this rapid growth occurred. However, it may be related to marked increases in total water discharge and total suspended sediment concentrations recorded between 1941 and 1947 (Morton and Pieper 1975).

1952-1953

50. By 1952, the shoreline of the BRDC delta had retreated significantly, while the old Freeport delta (not shown in Figure 28) eroded to a position nearly coincidental with the original 1887 shoreline (Figure 30). Retreat of the BRDC delta initially began in 1949, as the result of a hurricane which made landfall at Freeport which caused a surge of approximately 8 ft (Bodine 1969). It is also suggested that major dam and reservoir development within the Brazos River Basin precipitated the decrease in size of the BRDC delta. This is supported by the findings of Mathewson and Minter (1976) who correlated major reservoir construction upstream with a reduction in the frequency of high discharge events, and the trapping of significant quantities of sand produced within the basin. They attributed increased recession at Sargent Beach, located 16 miles west of the BRDC, to these factors.

1956-1957

51. Continued recession of the BRDC delta occurred (Figure 28). By 1957 it had reached the approximate position which it presently maintains (Figure 28). As a result of upstream reservoir construction prior to 1957 the quantity of sand transported by the Brazos River had been reduced to near constant values, and was little affected by subsequent reservoir development.

1962

52. Photos taken by the Corps nine months after Hurricane Carla indicate that sediments removed from the delta during the storm were reshaped,

thus, strongly skewing the subaerial part of the delta to the west (Seelig and Sorensen 1973a; Figure 28).

<u>1965-1971</u>

53. Air reconnaisance photos show that the BRDC delta continued to migrate westward (Figure 28).

<u>1978-1983</u>

54. Minor westward growth of the delta occurred between 1971 and 1983 (Figure 28). It is suggested that this progressive westward migration resulted from the dominance of net westerly transport over the reduced sediment load of the Brazos River.

Sediment Volume Changes

55. The volume of sediment stored in the BRDC delta was quantitatively determined by using hydrographic surveys for 1929, 1931 through 1934, 1937, and 1985. Source information for these surveys is given in Table B2. The method used to calculate the volume changes is described by Dean and Walton (1973). Figure 31 is an illustration of this procedure for an idealized case.

56. The first step in the calculation of the quantity of material stored in the delta involves the construction of idealized no-inlet contour lines. It is assumed that the natural topography of the coast without the inlet can be represented by shore-parallel contours. The NOS surveys

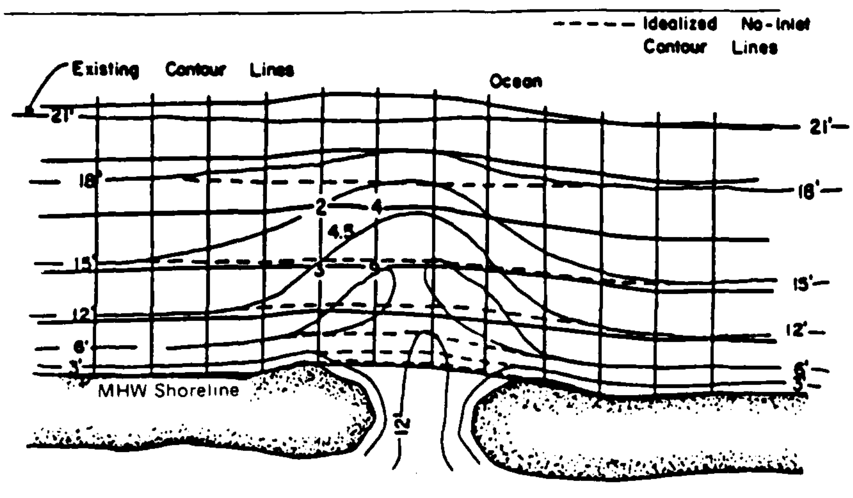


Figure 31. Procedure used to calculate the volume of sand stored in the BRDC delta. Illustration is for an idealized case (from Dean and Walton 1973)

conducted from 1855 indicate that this condition was satisfied for the study area prior to construction of the BRDC, thus validating this assumption (Figure 28). A square-grid system is then superimposed on a map containing the idealized no-inlet hydrography and the actual hydrography. Depth differences between the idealized and actual bathymetry are calculated for each grid intersection, and the average depth difference for each grid square is multiplied by the grid-square area to yield the volume of delta sediment contained within that grid cell. The volumes are then summed over the entire delta to arrive at the total volume of sediment stored in the delta. The area of each grid cell used in this analysis was 10^6 sq ft.

57. The six surveys chosen for the volumetric analysis comprise the entire hydrographic data base for the BRDC delta. The data for 1931 through 1934 do not extend to the western edge of the delta; therefore, bathymetric contours were extrapolated in this area. In addition, elevation data above mlw were not provided so that the volumes of subaerial material stored to the southwest of the river mouth could not be calculated. As a result, some error was introduced into the analysis. Dean and Walton (1973) calculated that the volumetric analysis method has an inherent error of less than 10 percent. With this in mind, volumes presented below represent conservative estimates of the material accumulated in the ebb-tidal delta region.

58. The 1929 survey taken prior to construction of the BRDC was used as the base map for each of the calculations. The results of the volumetric analysis were used to construct a plot of cumulative accretion from 1929 to 1985 (Figure 32). During the two years after construction of the BRDC the delta grew rapidly, reaching a volume of 10,820,000 cu yd by 1931. The area of the delta became progressively greater, and by 1932 the volume of the delta had increased to 14,790,000 cu yd. By 1933 the volume had increased to 17,030,000 cu yd with subaerial deposits flanking the channel on both sides. Volumetric calculations for 1934 indicate a small decrease to 16,380,000 cu yd. Odem (1953) shows that the entire delta thinned and migrated westward during this period. A surge of 10.9 ft which resulted from Hurricane Carla in 1961 (Bodine 1969) is believed to be responsible for this redistribution of sediment on the delta. Data from the hydrographic survey taken in 1937 show that the delta developed a triangular shape, and increased rapidly to a volume of 32,240,000 cu yd. The survey conducted for this study in February 1985 indicates that the volume increased to 35,970,000 cu yd.

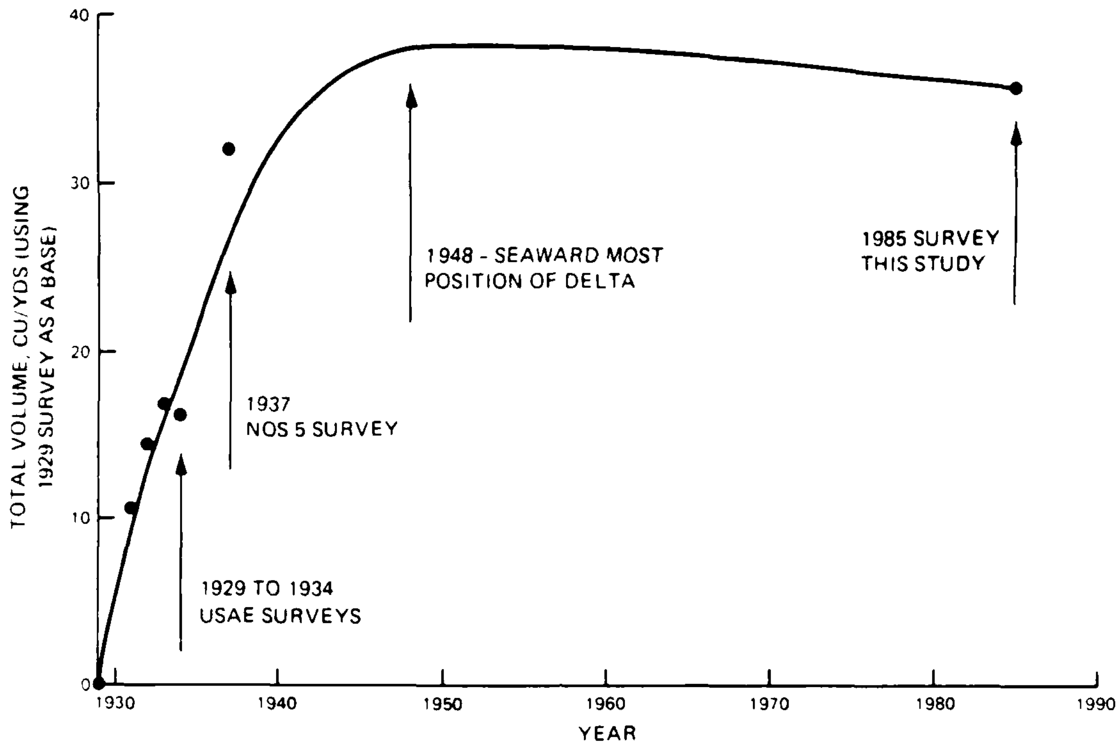


Figure 32. Cumulative growth of BRDC delta, 1929-1985

Although the volume of subaerial deposits could not be calculated for this study, it is important to note that these deposits represent a significant sediment sink at the mouth of the river. The area of subaerial deposits at the mouth of the BRDC was studied by Odem (1953). He estimated the total accumulation of subaerial deposits between 1929 and 1952 to be 1,210 acres (Figure 33).

59. The plot of cumulative delta accretion (Figure 32) indicates a period of rapid delta growth during the first 8 years, followed by a much longer period of slower delta growth. Simple considerations suggest that initial development of the delta was the result of relocation of the Brazos River mouth. The early period of rapid delta growth can be attributed to an abundant sediment supply from the erosion of the old Freeport delta, and the marked increases in total water discharge and total suspended sediment concentrations reported by Mathewson and Minter (1976) and Morton (1975). The triangular shape and extensive seaward protrusion of the delta during the first 19 years strongly suggest that fluvial processes were dominant over the Gulf processes. Similar delta morphologies have been found by Komar (1973)

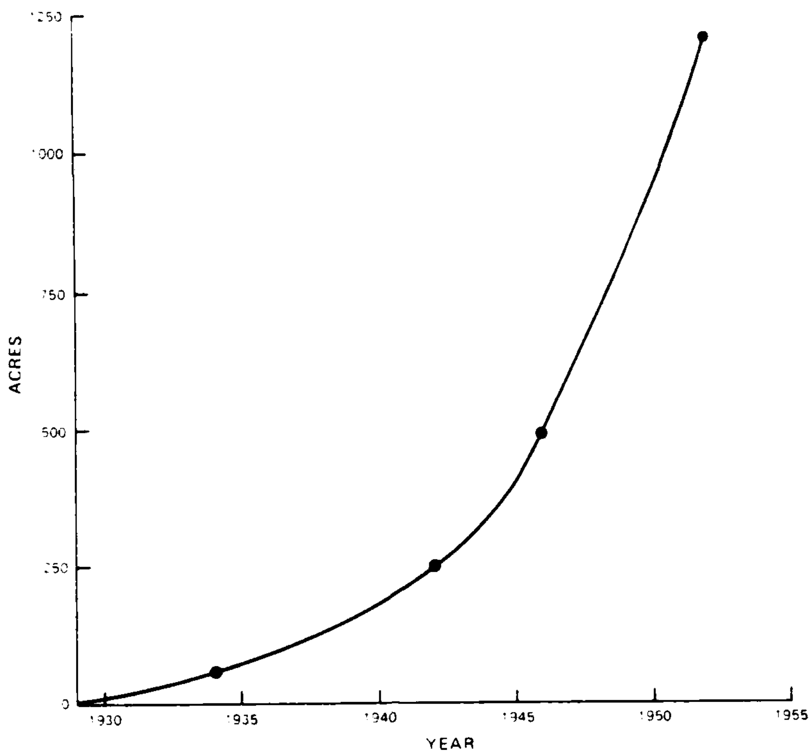


Figure 33. Cumulative subaerial growth of the BRDC delta (from Odem 1953)

and Wright and Coleman (1973), either in areas where the wave energy flux is low or river sediment supply is too high for the existing waves to remove sediment away from the river mouth. The following period of decreased delta growth can be attributed to a reduction in the available sediment supply to the coast by the Brazos River. As discussed by Mathewson and Minter (1976), the sediment load and frequency of high discharge events were decreased by dam and reservoir construction within the Brazos River Basin. These changes in the river hydrography shifted the delta to a system dominated by Gulf processes, causing a landward retreat of the delta and a smoothing out of the shoreline. Littoral and fluvial sediments are transported by the wave energy flux, and the net westerly longshore transport redistributes the delta sediments to the west.

Longshore Transport Estimates

60. By the use of LEO data from 1974 to 1980 (Schneider 1981), longshore-sediment transport estimates were developed for eight sites along

the Texas coast (Figure 34; Sherlock and Szuwalski 1985.) These estimates were derived using two methods. The first method, commonly called the Breaker Observation method, is outlined in the Shore Protection Manual (1984). This method obtains transport values based on the following equation for P_{ls}, the longshore energy flux factor:

$$P_{ls} = (\rho g/16) \times (H^2) \times Cg \times \sin(2\alpha) \qquad (1)$$

where

P_{ls} units = ft-lb/sec/ft of beachfront

ρ = density of water

H = breaking wave height

Cg = group velocity = $8.025 \times H^{0.5}$

α = incident breaking wave angle

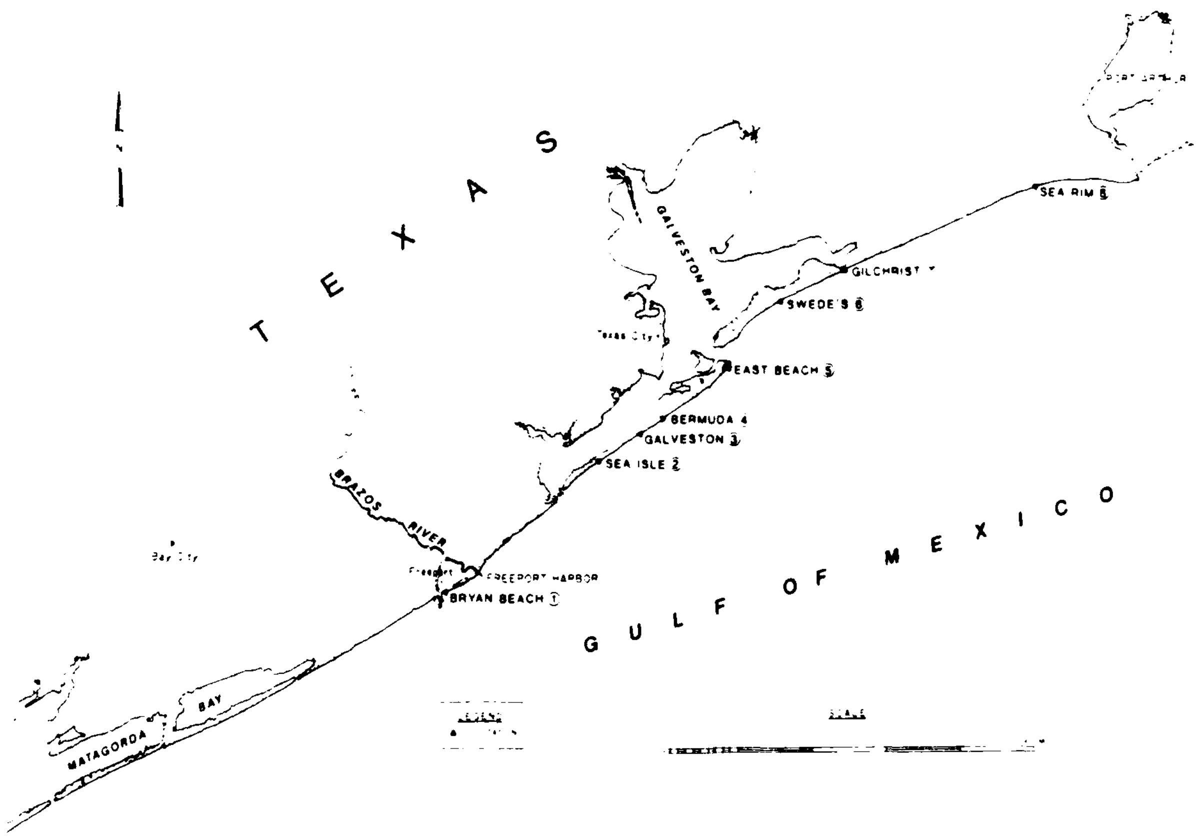


Figure 34. LEO sites used for sediment transport estimates (numbered 1 through 8)

61. The second method used to estimate the amount of sediment transport was the Current Observation method. This method utilizes the procedures outlined in CETA 80-3 (Walton 1980). The equation uses breaker wave height, longshore current velocity, and surf zone width to determine P_{ls} . It has the following form:

$$P_{ls} = \rho \times g \times H \times WSZ \times VLEO \times CF/((5 \times 3.14/2) \times VLH) \qquad (2)$$

where

WSZ = width of surf zone; $(d_b/A)^{1.5}$

d_b = wave breaking depth

A = beach profile factor

VLEO = average longshore current

CF = friction factor = 0.006

VLH = 0.2 × (X/WSZ) - 0.714 × (X/WSZ) × ln (X/WSZ)

X = distance from the beach to the dye patch

For both methods, the longshore sediment transport Q is computed by using the following equation:

$$Q \text{ (cu yd/yr)} = 7{,}500 \times P_{ls} \qquad (3)$$

62. A significant problem developed when using the LEO data to calculate sediment transport for the Current Observation method. In a sizable portion of the LEO data, the width of the surf zone (WSZ) appeared to be grossly overestimated by observers. Since WSZ is an integral part of the equation, a means to correct the surf zone width was developed. By using the following equation for an equilibrium beach profile, WSZ was calculated:

$$y = A \times X^{2/3} \qquad (4)$$

where

y = depth, ft

A = beach profile factor; a function of grain size ($ft^{1/3}$)

X = distance, ft

To find the width of the surf zone for a given size of breaking wave, let $y = d_b$ (depth of breaking), and $d_b = 1.28\ H_b$ (from breaking wave theory).

Letting WSZ = X , and substituting and solving Equation 3 for WSZ , yields the following:

$$WSZ = (D_b/A)^{1.5} = (1.28\ H_b/A)^{1.5} \tag{5}$$

In this case the mean grain size was assumed to be 0.15 mm, corresponding to a beach-profile factor value of 0.1605 $ft^{1/3}$.

63. A second factor to be considered in computing the rate of sediment transport using the LEO data was differing numbers of observations in each month. To overcome this bias in the data set, a method was developed to compute the transport on a monthly basis. The transport values for each month were summed over the entire period, and then divided by the total number of observations for that month; this gave the average transport for each month. The monthly values were then summed to give a yearly sediment transport rate. This method reduced the possibility of biasing the results.

64. Average sediment transport rates (Q) for each of the eight LEO sites (Figure 34) are shown in Table 3. For additional information, Table 4 lists the number of LEO observations per month and the time period over which the data were collected.

65. Table 3 shows that the Breaker Observation method consistently predicts higher transport rates than the Current Observation method. This is a result of the way in which the energy of the breaking wave is calculated and transmitted. In the Breaker Observation method the energy is calculated for a single point and the breaker wave height is squared. In the Current Observation method, the energy is transmitted across the entire surf zone and the breaker wave height is multiplied by the width of the surf zone.

66. Table 3 also indicates that potential sediment transport values for the Gilchrist site are significantly higher than the values at any of the other sites. It is believed that this occurred because the LEO observer(s) at Gilchrist consistently overestimated wave height. The average wave height for all the observations taken at Gilchrist was 3.54 ft, while at the remaining sites the average wave height was 1.90 ft. This increase in wave height would account for the anomalous sediment transport potential calculated at Gilchrist. As a result, the Gilchrist LEO data were removed from further calculations. The LEO data at the Swedes location were not collected from September through November, causing a seasonal bias in the yearly transport

Table 3

Average Sediment Transport from LEO Data Using the Breaker Observation Method (1) and Current Observation Method (2). All units are 1,000 cu yd/year

Location		Net	East	West	Gross
Bryan Beach	(1)	57 W	94	151	245
	(2)	49 W	63	112	175
Sea Isle	(1)	68 W	231	299	530
	(2)	43 W	202	245	447
Galveston	(1)	16 W	110	126	236
	(2)	67 W	63	130	193
Bermuda	(1)	184 W	176	359	535
	(2)	58 W	221	279	500
East Beach	(1)	8 W	61	70	131
	(2)	13 E	67	54	121
Swede's	(1)	5 W	114	120	234
	(2)	106 W	59	165	224
Gilchrist	(1)	285 E	847	562	1,410
	(2)	452 W	53	505	558
Sea Rim	(1)	8 W	69	77	146
	(2)	33 E	109	76	185

Table 4

Number of LEO Observations Used in the Sediment Transport Calculations

Breaker Observation Method (1) and the Current Observation Method (2)

Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Bryan Beach	(1)	11	11	11	13	17	6	7	6	9	2	20	15	128
11/74-5/76	(2)	11	11	11	13	17	6	7	6	8	2	20	15	127
Sea Isle	(1)	32	20	29	27	16	6	16	14	14	19	8	14	215
11/74-4/76	(2)	27	19	26	25	16	6	14	10	13	18	7	13	194
Galveston	(1)	73	41	85	74	81	79	97	93	70	71	72	91	927
11/74-8/80	(2)	68	37	77	69	74	68	90	85	69	66	64	86	853
Bermuda	(1)	33	20	29	28	18	12	16	16	20	20	22	24	258
11/74-4/76	(2)	27	17	29	23	16	8	14	14	19	19	19	23	228
East Beach	(1)	10	12	14	31	31	28	29	29	27	15	12	13	251
4/72-4/73	(2)	6	11	13	24	21	23	27	22	22	12	8	11	200
Swede's	(1)	29	16	9	21	31	41	3	13	0	0	0	10	173
12/74-6/76	(2)	29	13	8	21	29	41	3	6	0	0	0	9	159
Sea Rim	(1)	22	36	59	54	52	51	44	47	44	54	39	54	556
7/75-6/79	(2)	18	27	51	48	44	44	40	41	37	50	31	39	470

rates (Table 4). Because of this, the values were not used for further calculations.

67. Results of the longshore-sediment transport computations for the remaining six sites indicate a net transport direction to the west (Table 3). Easterly net transport was predicted only twice by the Current Observation method at East Beach and Sea Rim. Net values using both methods ranged from 8,000 to 184,000 cu yd/year. The majority of the transport values were between 40,000 and 70,000 cu yd/year, and for the two sites closest to the BRDC the range in net sediment transport was 43,000 to 68,000 cu yd/year. Gross transport estimates ranged between 121,000 and 535,000 cu yd/year with an average of 278,000 cu yd/year.

68. A summary of the net monthly sediment transport values calculated from LEO data collected at Bryan Beach, located approximately 2 miles southeast of the BRDC, is shown in Table 5. The data indicate seasonal reversals in longshore transport direction. Westerly longshore transport took place from October through April. During May, June, and September, transport was slightly toward the west, and easterly transport took place in July and

Table 5

Average Monthly Sediment Transport for Bryan Beach,
Units are in 1,000 cu yd/month

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
8 W	11 W	17 W	11 W	2 W	1 W	10 E	15 E	2 W	15 W	10 W	4 W

August. Data collected at the other LEO sites show similar seasonal transport patterns. These results are consistent with seasonal drift distributions discussed in the SWG Shore Erosion Study (in preparation).

69. Seelig and Sorensen (1973a) present littoral drift rates for Sargent Beach, located approximately 16 miles east of the BRDC; they discuss longshore transport rates calculated using five different techniques. A summary of their results is shown in Table 6. In techniques 1 through 4,

Table 6

Sediment Transport Potential Near Sargent Beach, Texas
(From Seelig and Sorensen 1973a). All units are 1,000 cu yd/year

Method	Net	East	West	Gross
Seelig (1)	30 W	318	348	666
Seelig (2)	11 W	124	135	259
Seelig (3)	14 W	289	303	592
Mason (4)	19 W	139	157	296
Mason (5)	19 to 89 W			296 to 998

hindcast deepwater waves were refracted into Sargent Beach by using the linear wave theory (Bretschneider and Gaul 1956). Littoral drift rates were assumed to be a function of the longshore energy in methods 1 and 4, and the formula of Savage (1959) was used to estimate the net and gross littoral transport. Method 2 utilized a relationship from Inman (Inman, Komar, and Bowen 1968) to determine the sediment transport potential, and Weggel's (unpublished report*)

* Weggel, J. R. 1973. "Curves of Net and Grass Alongshore Wave Energy Versus Shoreline Orientation," (unpublished report), Coastal Engineering Research Center, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

trial and error breaking wave method was used in method 3. Longshore transport rates were calculated by observing spit growth at Brown Cedar Cut in method 5. Successive surveys from Brown Cedar Cut (20 miles southwest of the BRDC) were compared and assumed to be a fraction of the littoral transport. Each of the above methods predict net sediment transport to the west. Net values range from 11,000 to 89,000 cu yd/year, and gross rates ranged from 296,000 to 998,000 cu yd/year.

70. Seelig and Sorensen (1973a) also present gross transport rates obtained from maintenance dredging records at the Freeport Harbor Entrance Channel. Using dredging records from 1967 to 1972, they estimated the gross longshore transport to be 1,184,000 cu yd/year. Carothers and Innis (1960) estimated the gross transport from dredging records to be 703,000 cu yd/year.

71. A recent study by SWG (US Army Engineer District, Galveston (in preparation)) entitled "The Galveston County Shore Erosion Study Feasibility Report and EIS", contains transport rates that have been determined by using wave-energy flux calculations from the Shore Protection Manual. Wave data were taken from 10-year records of the SSMO. Wave refraction analyses at the numbered sites in Figure 35 were used in the energy flux computations. The results are presented in Table 7. In addition, the Galveston District Shore Erosion Study presents estimates of littoral drift due to wind generated currents. These values were calculated using the Einstein-Brown equation (Einstein 1950) which assumes a single grain size of 0.20 mm. The calculated values were 45,000 to 50,000 cu yd/year to the west. Results from this analysis were added directly to the net littoral drift values calculated by using the wave energy flux method. This technique is generally not used in sediment transport calculations, and the report did not contain sufficient information to evaluate how it was used in the analysis. Consequently, the littoral drift values due to wind are not included in Table 7. It is worth noting, however, that the Current Observation method used in this report implicitly includes wind effects.

72. Results from the Galveston County Shore Erosion Study indicate that the direction of net transport changes over the study area, however, the gross sediment transport is fairly consistent at sites 11 through 16, ranging from 301,000 to 375,000 cu yd/year (Table 7). Most important are the net values at sites 15 and 16, which are closest to the Brazos River mouth. Site 15, with net sediment transport of 49,000 cu yd/year to the west, is 4 miles

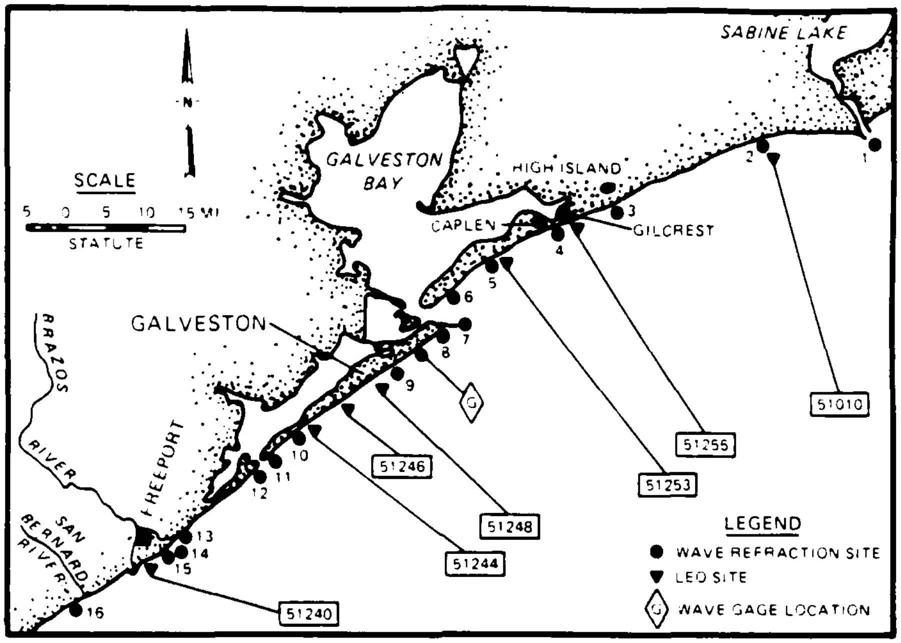


Figure 35. Wave refraction and LEO sites (from the Galveston County Shore Erosion Study)

Table 7

Summary of Littoral Drift Predictions in Galveston County

(From the Galveston County Shore Erosion Study.)

Units are 1,000 cu yd/year

LEO Stations	Location	Net	East	West	Gross
2	Clam Lake	25 W	17	43	60
3	High Island	57 W	53	110	163
4	Crystal Beach	51 W	61	112	173
5	Swede's	55 W	55	110	165
6	Bolivar Road	2 W	13	15	28
8	12th Street	17 E	104	87	191
9	Scholes Field	11 W	138	126	264
10	Sea Isle	26 E	200	175	375
11	East of San Luis Pass	23 E	166	143	309
12	West of San Luis Pass	78 E	190	112	302
13	Oyster Creek	56 E	197	141	338
15	West of Freeport	49 W	130	180	310
16	San Bernard River	39 W	144	182	326

northeast of the Brazos River mouth. Site 16, with net sediment transport of 39,000 cu yd/year to the west, is 9 miles southwest of the Brazos River mouth.

73. These data agree well with the data from the LEO site closest to the Brazos River mouth, Bryan Beach, shown in Table 8. This site is two miles to the northeast. The LEO net-sediment transport values at Bryan Beach from the breaker observation and current observation methods, were 49,000 and 57,000 cu yd/year to the west. Gross values were lower than SWG estimated. These values averaged values 245,000 and 175,000 cu yd/year for each method. Disagreement between the SWG date and LEO data at sites to the northeast of the Brazos River mouth is likely due to refraction effects. Sites 8, 11, 12, and 13 which are used by SWG are close to inlets or deltas that can cause significant local refraction effects.

Table 8

Summary of Average Sediment Transport Data at Sites Closest to the Brazos River Mouth (Units are 1,000 cu yd/yr), Breaker Observation Method (1) and the Current Observation (2)

Source/Site	Net	Gross
LEO/Bryan Beach (1)	57 W	245
Bryan Beach (2)	49 W	175
Seelig and Sorensen, Mason and Sorensen/		
Sargent Beach	11-30 W	296-998
Dredging Records		
Freeport		703-1,184
Galveston District - Refraction		
West of Freeport	49 W	310
San Bernard River	39 W	325

74. Seelig and Sorensen's (1973a) net transport data for Sargent Beach (11,000 to 30,000 cu yd/year to the west) are generally lower than the LEO data and the Galveston District wave data near the mouth of the Brazos River. The agreement between the data sets is improved when the study by Carothers and Innis (1960) is examined. This study states that the net westerly littoral drift decreases as one moves southwest towards Corpus Christi.

75. Estimates of gross transport from Seelig and Sorensen (1973a) and Mason and Sorensen (1971) fall between 260,000 and 1,000,000 cu yd/year, with most of the data being between 260,000 and 666,000 cu yd/year. This is somewhat higher than the Galveston District data and the majority of the LEO data.

76. The gross sediment-transport values from the dredging records at Freeport reported by Seelig and Sorensen (1973a) and Carothers and Innis (1960) indicate generally higher values, 1,184,000 and 703,000 cu yd/year, respectively, than do most of the other estimates. This is not surprising because shoaling rates within a channel also include sediment transported into the channel from waves interior sources, sloughing from side slopes, overdredging, and channel deepening effects, in addition to the longshore sediment transport.

Numerical Hydraulic Model

Existing river discharge and sediment load information

77. According to Seelig and Sorensen (1973a), the Brazos River siltload averages somewhere within the 1,000- to 3,000-ppm range. The USGS stream flow records for the water year 1966 through 1967 show that the monthly mean discharge of the lower Brazos River ranged from 600 cu ft/sec in March 1967 to 5,100 cu ft/sec in October 1966, and the monthly mean suspended sediment loads ranged from 50 tons per day in March 1967 to 10,600 tons per day in May 1967 (Figure 36). The flow-duration, US Geological Survey (1975), curve for mean daily discharges at Richmond, Texas, for the water years 1966 through 1970 is shown in Figure 37. The Richmond gaging station is located on the Brazos River approximately 92 miles upstream from the Gulf of Mexico. The sediment rating curve, USGS (1975) for the Brazos River at Richmond, which was developed from daily sediment load measurements during the 1969 and 1970 water years is shown in Figure 38.

78. Seelig and Sorensen (1973a) estimated the suspended load in the lower Brazos River to be about 300,000 to 400,000 cu yd/year. They also estimated that the bed load contributes an additional 150,000 to 200,000 cu yd/year to the sediment transport regime. Based on the bathymetric surveys taken in August 1982 and December 1984, the shoaled material in the diversion channel and offshore bar channel totaled about 330,000 cu yd of

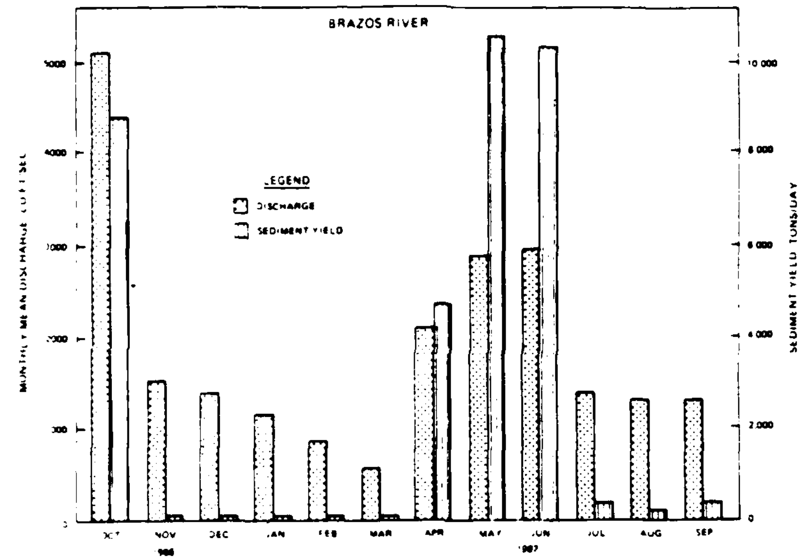


Figure 36. Brazos River discharge and sediment yield, 1966-1967

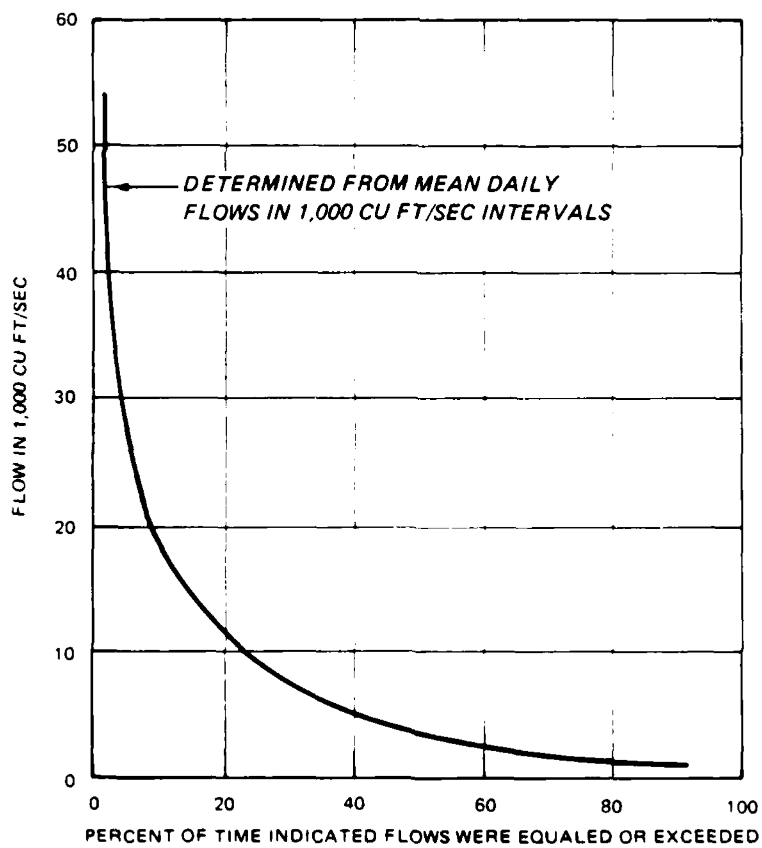


Figure 37. Flow-duration curve for the Brazos River at Richmond

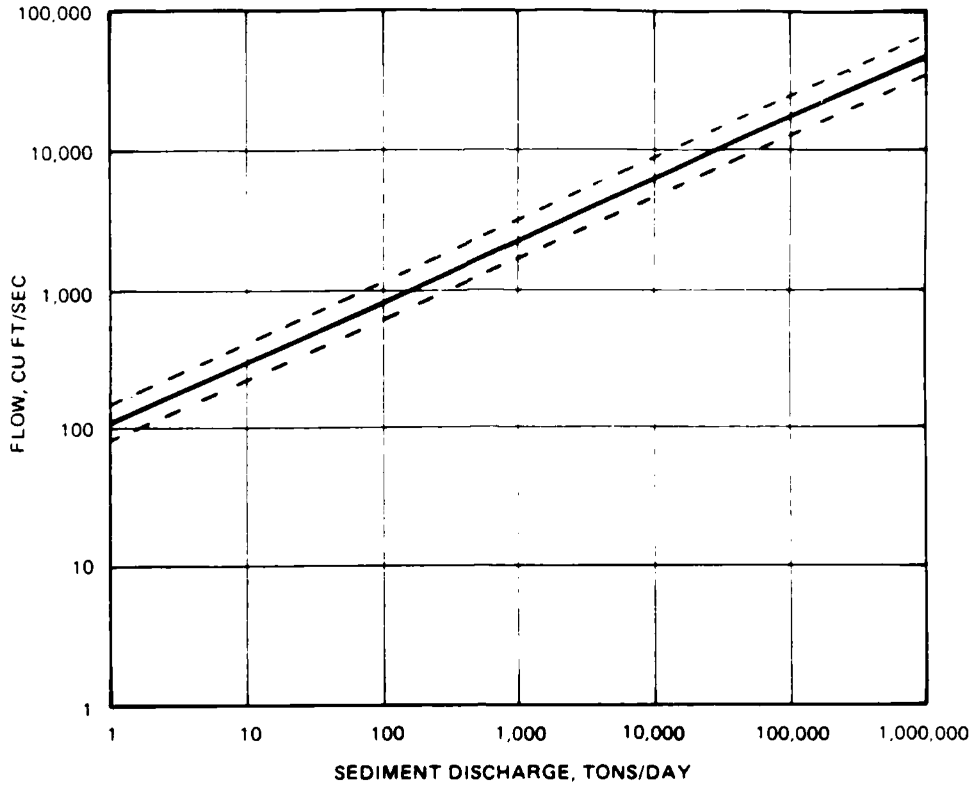


Figure 38. Sediment-rating curve for the Brazos River at Richmond

sediment with about 78 percent (261,000 cu yd) of that in the diversion channel between the floodgates and the Gulf and about 22 percent (72,000 cu yd) in the offshore bar channel (Figure 23). For the basic 12-ft-deep by 125-ft-wide diversion channel, the shoaling estimate of 261,000 cu yd annually is as good as can be obtained without an intensive field and modeling effort.

Laterally averaged estuarine model for sediment transport model description

79. The two-dimensional (2-D), laterally averaged numerical sediment transport model (LAEMSED) was used to predict sediment transport along the BRDC for various dredged channel dimensions. The basic set of flow and transport equations that are solved in LAEMSED are statements of the conservation of mass and momentum of the flow field plus the conservation of heat, salt, and suspended sediment content of the water's body. The governing equations are developed by first performing a temporal averaging of the three-dimensional (3-D) equations for laminar flow. Boussinesq's eddy coefficient

concept is then used to account for the effect of turbulence in the flow field. Next, the time-averaged equations are averaged over the channel width and finally over each individual vertical layer to yield conservation equations that are solved for each layer in the water column.

80. Basic LAEMSED assumptions, in addition to the reduced dimensionality, are that the Boussinesq approximation is applicable and that vertical accelerations are negligible so that the pressure can be considered hydrostatic. In addition, the concept of eddy coefficients is used to represent the effect of both time averaging, as previously noted, and spatial averaging of the equations. The horizontal dispersion coefficients are assumed to be constant, whereas the vertical dispersion coefficients are dependent upon the stratification as reflected by the Richardson Number.

81. Finite difference techniques are used to solve the governing equations. The particular scheme employed is structured such that the water-surface elevations are computed implicitly. Using the new water-surface elevations, the longitudinal component of the flow velocity is then explicitly computed from the longitudinal momentum equation. As in other hydrostatic models, the vertical component of the velocity is computed from the continuity equation. The solution begins at the channel bottom and progresses up the layers. With the flow field computed, the water temperature, salt, and suspended sediment concentrations are then computed from their respective transport equations in a semi-implicit manner. Details of the numerical solution scheme can be found in Edinger and Buchak (1981).

82. The routines in LAEMSED that compute the exchange of sediment between the bed and the water column are modifications of those routines found in a vertically averaged sediment transport model called Sediment Transport in Unsteady Two-Dimensional Flows, Horizontal Plane (STUDH) (Thomas and McAnally 1985). The sediment may be treated as either cohesive, which is referred to as clay, or noncohesive, which is considered sand. A single, effective grain size is considered for each.

Required model input

83. The major data input required by LAEMSED is the geometry data describing the system. As the center of each computational cell, the width of the channel must be prescribed. For the study described herein, these were obtained from hydrographic survey data. Additional data required are the boundary conditions that drive the internal flow field. At a river boundary,

a discharge must be prescribed, whereas at an ocean boundary the water level must be input. In addition, at inflow boundaries vertical distributions of temperature, salinity, and suspended sediment concentrations must be prescribed.

84. In addition to the water column data described above, information about the sediment and the initial bed structure must be input. A constant settling velocity is input for noncohesive material (sand); whereas, an option can be invoked to compute settling velocities for cohesive material by using an empirically based equation. Default values for the many characteristics of the different type layers that make up the sediment bed are provided in LAEMSED, e.g., the dry density of a freshly deposited layer of sediment is defaulted to 90 kg/m^3. However, all of these values can be changed through input data if desired.

Model test conditions

85. To address the impact of the proposed 14, 16, 18, and 20-ft project depths on annual maintenance dredging requirements, as well as the impact of 2, 4, 6, and 8 ft of advance maintenance added to the 12-ft project, the numerical sediment transport model LAEMSED was applied to the BRDC. Although a fully verified modeling effort was beyond the scope of this investigation, the use of LAEMSED using reasonable input parameters allowed for an estimate of the shoaling potential in the diversion channel as a function of channel depth and river discharge.

86. At the Gulf of Mexico, each model run used a tide range of 1.5 ft. The duration of each run was two tidal cycles (50 hr). Three river discharges of 5,000, 10,000, and 20,000 cu ft/sec were tested. For the test with the Brazos River discharge at 5,000 cu ft/sec, the Dow's Chemical Company discharge was 2,000 cu ft/sec. For the tests with the Brazos River discharges at 10,000 and 20,000 cu ft/sec the Dow discharge was 4,000 cu ft/sec. For all tests, the salinity of the Dow discharge was 30 ppt. For all tests, the river discharge sediment concentration was 100 ppm. The sediment-fall velocity was 0.003 m/sec. The critical shear stress for deposition was 0.06 $Newton/m^2$. The model was constructed using 8 vertical layers, each 3 ft thick. Thus, the model could accommodate depths as great as 24 ft. Tests were conducted using a 12-ft-deep diversion channel, referred to as the base test, a 15-ft-deep diversion channel, an 18-ft-deep diversion channel, and a 21-ft-deep diversion channel. The model layout, shown in Figure 39, included 48 cells along the

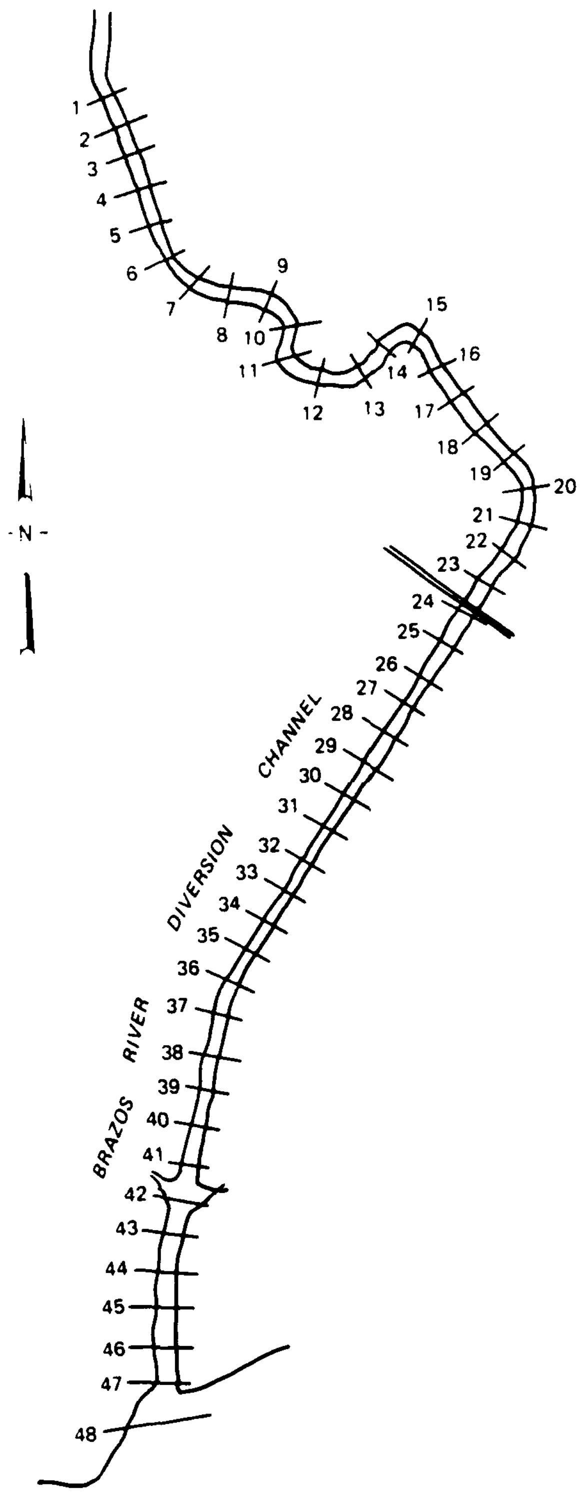


Figure 39. LAEMSED grid

.ower Brazos River, each one-fourth mile in length and each containing 8-vertical computational layers. The model encompassed the lower Brazos River reach from the Gulf entrance to a point about 12 miles upstream.

87. The model conditions tested with LAEMSED are summarized in Table 9.

Table 9

Model Conditions Tested with LAEMSED

Test	Tide Range ft	River Discharge cu ft/sec	Dow Discharge cu ft/sec	Channel Depth ft
1	1.5	5,000	2,000	12
2	1.5	5,000	2,000	15
3	1.5	5,000	2,000	18
4	1.5	5,000	2,000	21
5	1.5	10,000	4,000	12
6	1.5	10,000	4,000	15
7	1.5	10,000	4,000	18
8	1.5	10,000	4,000	21
9	1.5	20,000	4,000	12
10	1.5	20,000	4,000	15
11	1.5	20,000	4,000	18
12	1.5	20,000	4,000	21

Model results

88. The first step in the shoaling analysis was to defi:. a shoaling ratio SR as

$$SR = \frac{I_p}{I_B} \tag{6}$$

where I_p equals diversion channel infill over a tidal cycle for the plan condition and I_B equals diversion channel infill over a tidal cycle for the base condition. The channel reach considered in this analysis was that portion of the landlocked diversion channel from the floodgates to the entrance.

89. The shoaling ratios for the tests conducted are summarized in Table 10.

Table 10

Shoaling Ratios Computed by LAEMSED for Three River Discharges

Test	Channel Depth ft	Shoaling Over a Tidal Cycle* cu yd	Shoaling Ratio
		Q = 5,000 cu ft/sec	
1	12	163	1.00
2	15	243	1.49
3	18	361	2.22
4	21	485	2.94
		Q = 10,000 cu ft/sec	
5	12	1765	1.00
6	15	2272	1.28
7	18	2575	1.45
8	21	3921	2.22
		Q = 20,000 cu ft/sec	
9	12	0	--
10	15	0	--
11	18	0	--
12	21	0	--

* Second tidal cycle of simulation.

90. As can be seen from Table 10, the shoaling which occurred at the 10,000 cu ft/sec discharge was about an order of magnitude greater than that for the 5,000 cu ft/sec discharge. Also, at the river discharge of 20,000 cu ft/sec, no deposition occurred along the diversion channel for any of the depths tested. The entire sediment load was carried into the Gulf entrance area.

91. The next step was to estimate representative shoaling rates over depth by (a) averaging the SR values obtained for the 5,000 and 10,000 cu ft/sec discharges, (b) interpolating to 1-ft depth increments, and (c) assigning the 12-ft depth shoaling rate the value of 261,000 cu yd/year. The resulting shoaling rates at incremental depths are cited as follows in Table 11.

Table 11

Shoaling Rates at Incremental Depths
Determined by LAEMSED

Depth ft	Shoaling Rate cy yd/year
12	261,000
13	295,000
14	328,000
15	362,000
16	401,000
17	440,000
18	479,000
19	544,000
20	630,000
21	673,000

92. To estimate the maintenance dredging required to reliably maintain project depths of 12, 14, 16, 18, and 20 ft throughout the year, the shoaling rates at the desired depths must be applied. To maintain the project at or near project depth throughout the year would probably require dredging much more often than annually. Therefore, the estimated maintenance dredging requirements for the diversion channel are as follows in Table 12:

Table 12

Estimated Annual Maintenance Dredging Requirements for BRDC
from GIWW Crossing to River Mouth

Project Depth ft	Maintenance Required cu yd/year
12	261,000
14	328,000
16	401,000
18	479,000
20	630,000

93. To estimate the maintenance dredging required for the 12-ft project with the addition of 2- to 8-ft advance maintenance, shoaling rates must be applied over the range of depth represented by advance maintenance. For example, if the advance maintenance is 6 ft, the resulting range of depth is 6 ft (12 to 18 ft), and the representative shoaling rate is estimated from the average of the shoaling rates between 12 and 18 ft depths. Therefore, by

using this approach, the diversion channel maintenance dredging estimates for the 12-ft project with advance maintenance added are as follows in Table 13:

Table 13

Estimated Annual Maintenance Dredging Requirements for 12-ft Project Depth with Advance Maintenance BRDC from GIWW Crossing to River Mouth

Project Depth ft	Advance Maintenance ft	Total Depth ft	Maintenance Required cu yd/year
12	0	12	261,000
12	2	14	295,000
12	4	16	329,000
12	6	18	366,000
12	8	20	415,000

Numerical Wave Refraction Model

Model description

94. The Regional Coastal Processes Wave Propagation Model (RCPWAVE) was used to predict wave propagation over the Brazos River offshore region. The computer program uses finite-difference approximations to predict propagation of linear monochromatic waves outside the surf zone. An empirical method is used to predict wave transformation inside the breaker zone. The RCPWAVE computes the finite-difference solutions on a grid system comprised of constant or variably sized cells. The processes of refraction and diffraction are treated in the model, which has been verified using laboratory and field data. For the program theory, documentation, and user's guide, the reader is referred to CERC Technical Report entitled "Regional Coastal Processes Numerical Modeling System; Report 1, RCPWAVE - A Linear Wave Propagation Model for Field Use," (Ebersole, Cialone, and Prater 1986).

95. Input to the model includes: (a) the deepwater wave characteristics (height, period, and direction) which describe the wave conditions to be simulated, (b) the geometry of the grid system, including the size and number of cells, and the stretching coefficients if variably sized cells are used, and (c) the bottom bathymetry for each grid cell. For each wave condition simulated, the program output contains a listing of the following wave characteristics: (a) indexes defining the surf zone location, (b) wave angles,

(c) wave heights, and (d) the magnitude of the wave phase function gradient.

Model setup

96. Prior to applying RCPWAVE, a finite-difference grid system encompassing the study area was developed. The grid was designed to cover the entire offshore region affected by the BRDC. The y-axis of the grid was drawn parallel to the trend of the coastline, stretching from 3.5 miles west of the Freeport jetties, past the Brazos and San Bernard Rivers, to Cedar Lakes (Figure 40). The x-axis was drawn nearly perpendicular to the bottom contours, extending seaward to the 60-ft depth contour. The accuracy of the model predictions partially depends on cell size, with smaller cells resulting in less error. For this reason, variably sized grid cells were chosen. Cell size decreased in the onshore direction and in the alongshore direction surrounding the mouth of the Brazos River (Figure 40). The grid was designed to produce fine resolution in the region of interest surrounding the BRDC.

97. The bathymetry required as input to the model was digitized from NOS nautical chart No. 11321 and 1985 survey data collected as part of this study. The water depths were entered as positive, nonzero values, and all grid cells occupying dry land were designated by zeros. Internally the model assigns a small water depth of 1.0 ft to dry land. The data were initially digitized on a course rectangular grid containing 31 cells in the longshore (y-) direction and 18 cells in the onshore (x-) direction. A computer program was used to interpolate the bathymetry to the finer grid used in the analysis (94 by 76, Figure 40). The interpolation program is discussed in detail in CERC Technical Report (Ebersole, Cialone, and Prater 1986).

98. The wave conditions simulated by RCPWAVE are listed in Table 14. Wave height and period statistics were taken from Thompson (1977), and incident wave angles were taken from Bretschneider and Gaul (1956).

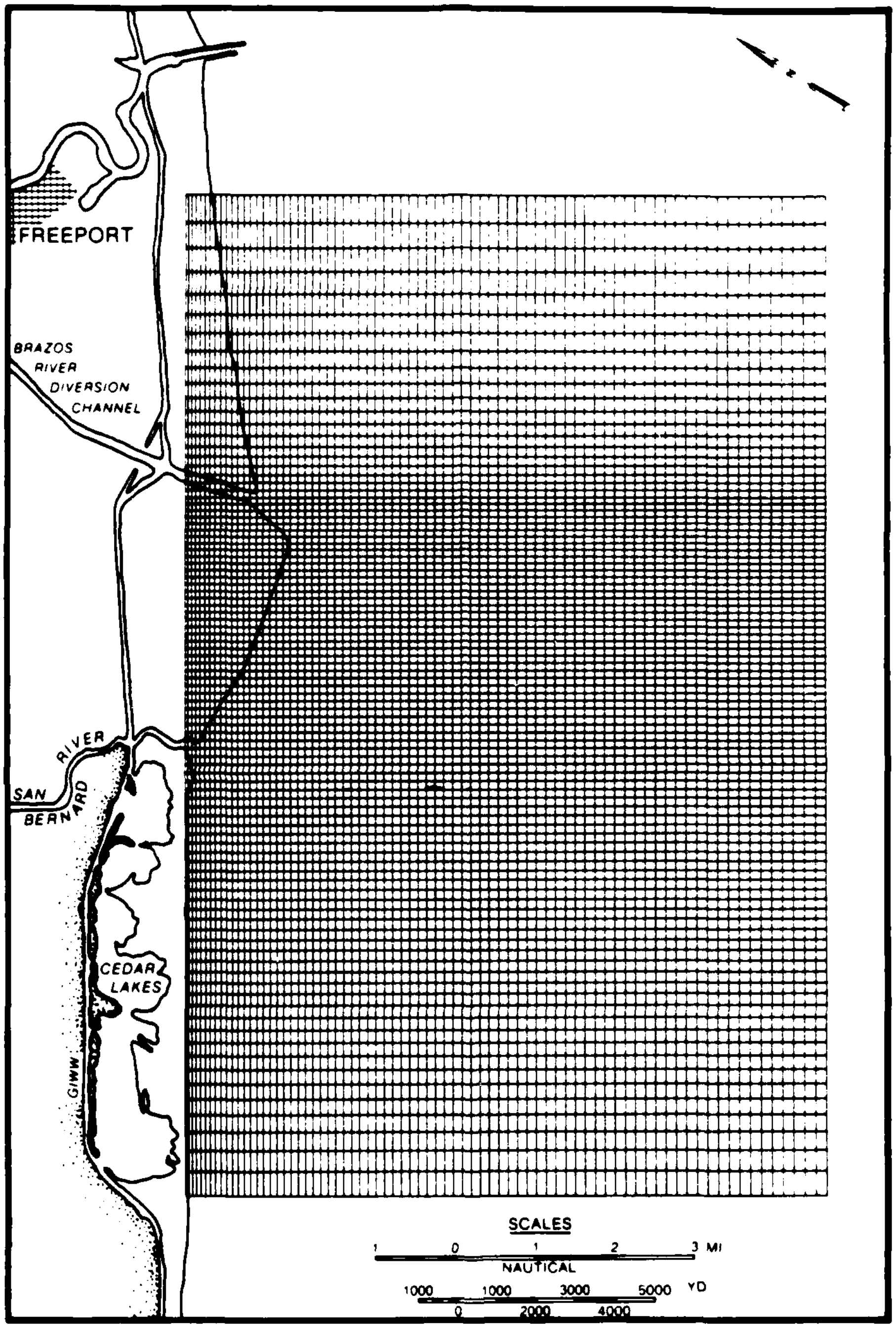


Figure 40. Finite-difference grid system encompassing offshore region affected by the BRDC, 94 by 76 grid

Table 14

Simulated Wave Conditions Used for RCPWAVE

θ_o Direction	θ_o degrees*	Wave Height ft	Wave Period sec
East-Southeast	32.0	2.5	3.0
	32.0	2.5, 3.5, and 4.5	6.0
	32.0	2.5	8.0
Southeast	13.0	3.5	3.0
	13.0	2.5, 3.5, 4.5, 5.5	6.0
	13.0	3.5	8.0
South	-32.0	2.5	3.0
	-32.0	2.5, 3.5, and 4.5	6.0
	-32.0	2.5	8.0

* Measured as the angle between the wave orthogonal and the offshore (x-) axis.

Model results

99. Figures 41, 42, and 43 are incident wave angle diagrams predicted by RCPWAVE, for identical height and period waves approaching from the east-southeast, southeast and south, respectively. There are only slight differences between each of the diagrams. Upon approaching the shoreline, waves from any direction tend to refract to a shore-normal direction. This tendency becomes stronger as wave period increases from 3 to 8 sec, such that 8-sec waves propagate straight onshore. This observation holds true for each of the incident wave angles. Little or no change occurred in the refraction as a function of wave height.

100. Most important are the refraction patterns around the delta and the mouth of the diversion channel. Incident waves from the east-southeast and southeast (Figures 41 and 42) tend to refract towards the northeast, in the lee of the delta (western side of delta). This has the effect of causing sediment transport towards the river mouth. Waves approaching the diversion channel are directed towards the western flank of the channel. Although, resolution of the model grid was not fine enough to predict wave propagation inside the mouth of the channel, it is suspected that waves striking the western flank are reflected to the northeast. Incident waves from the south also refract in the lee of the delta (Figure 43). At the river mouth these waves refract to propagate directly up the channel.

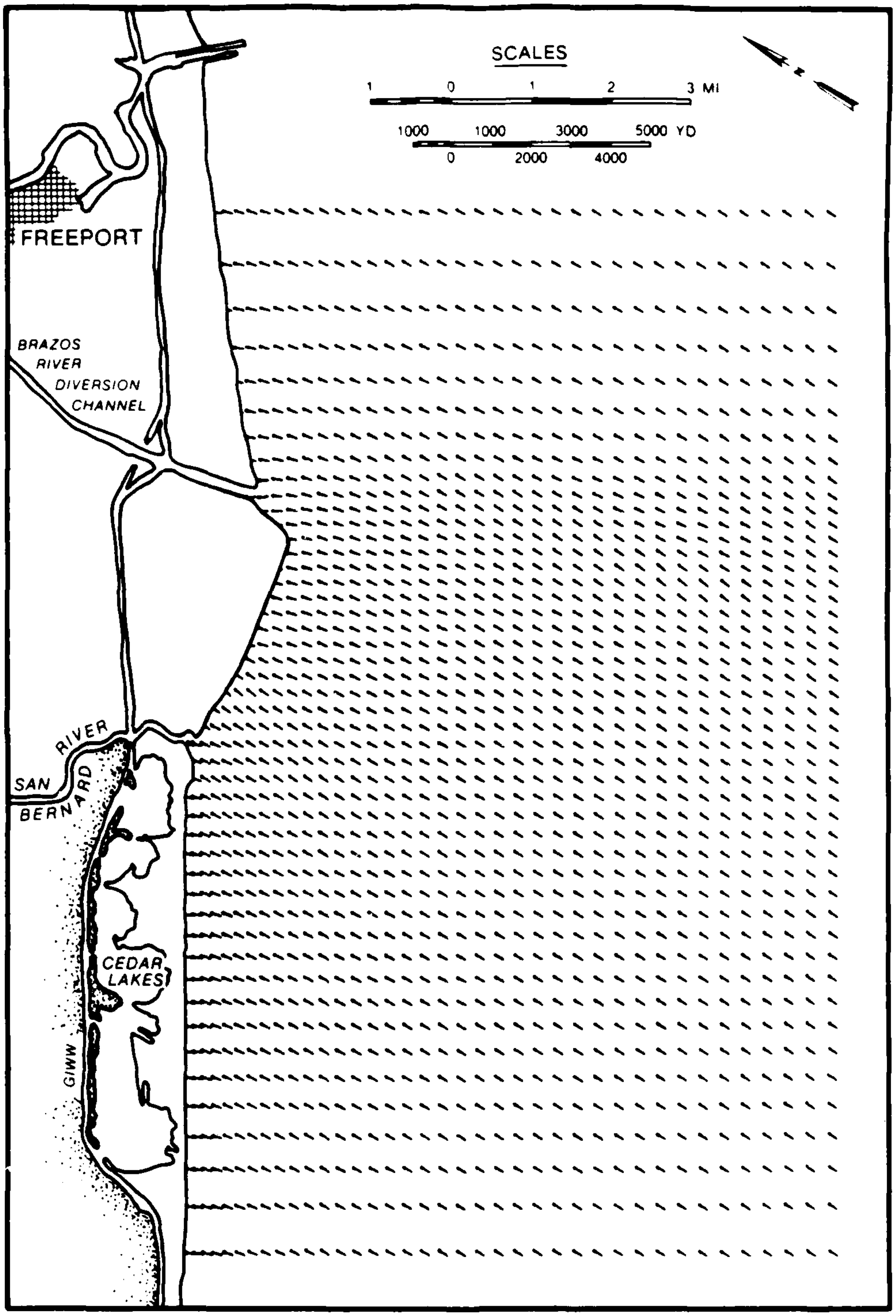


Figure 41. Incident wave angles predicted by RCPWAVE, H_o = 2.5 ft, θ_o = ESE , T = 6 sec

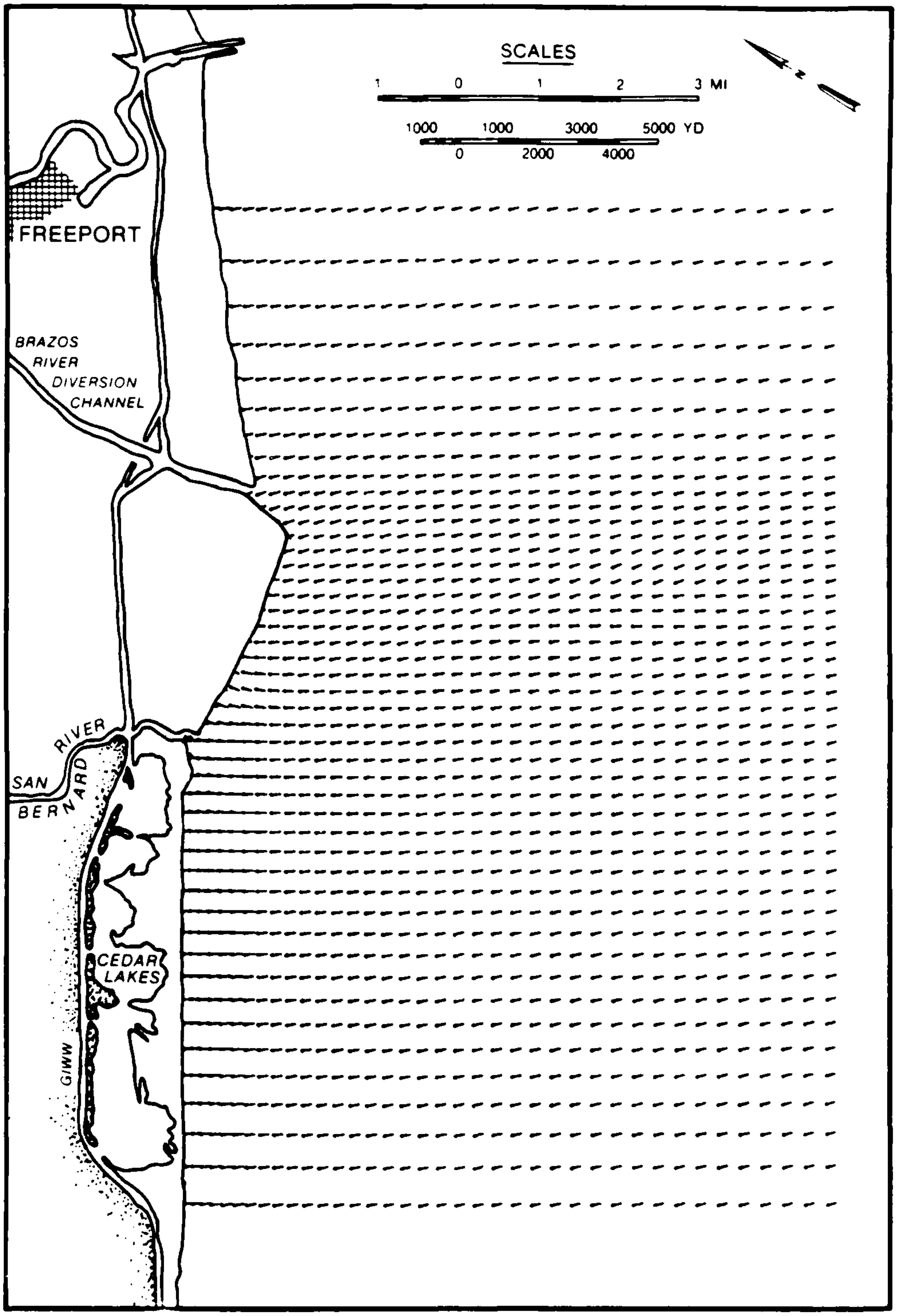


Figure 42. Incident wave angles predicted by RCPWAVE, H_o = 2.5 ft, θ_o = SE , T = 6 sec

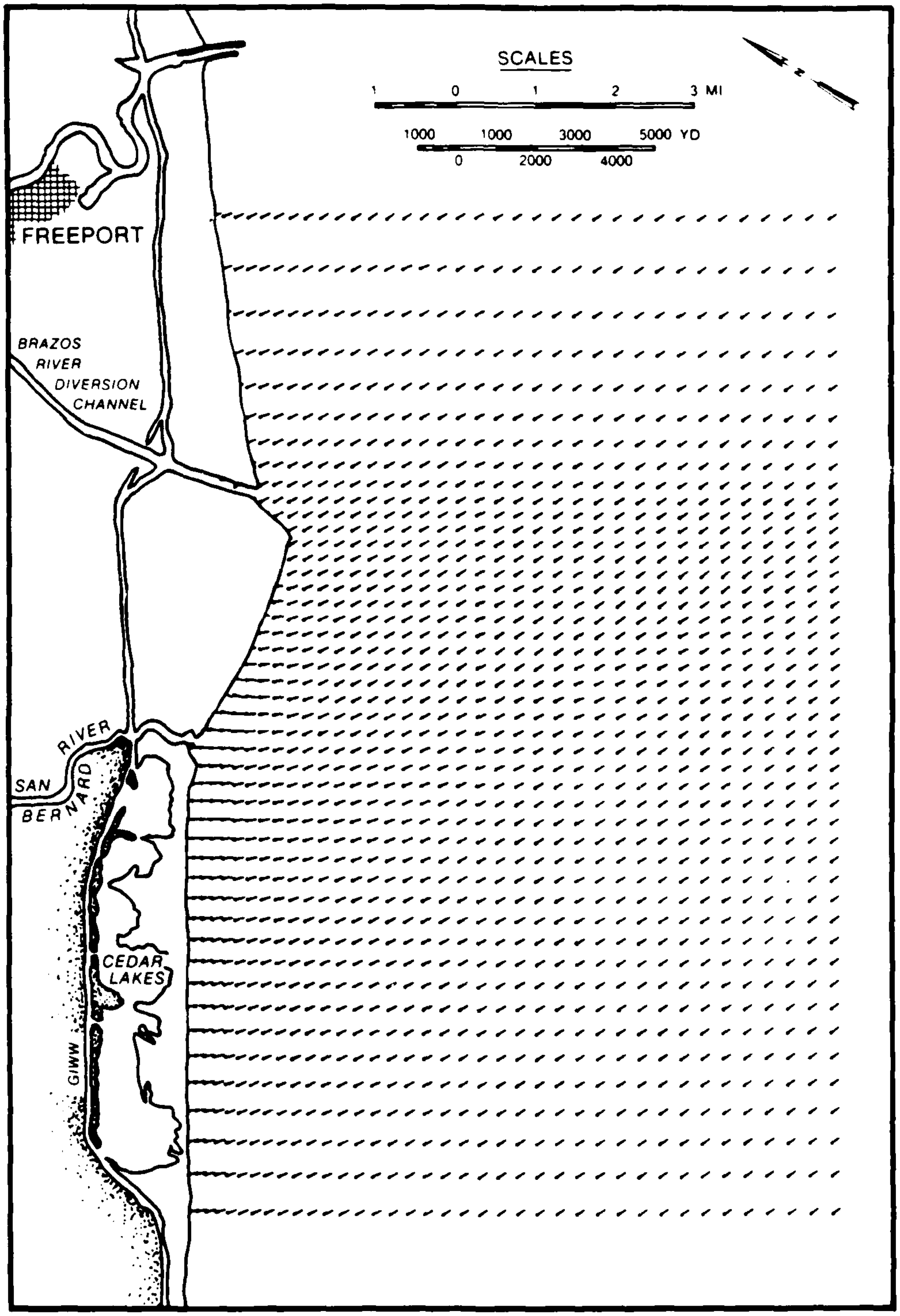


Figure 43. Incident wave angles predicted by RCPWAVE, H_o = 2.5 ft, θ_o = S , T = 6 sec

Shoaling Rate Prediction

101. The feasibility of maintaining the BRDC as a navigable waterway was determined through an analysis of shoaling rates in the design channel. The volume of dredge material required to maintain the project depth, the duration of the project depth, and the frequency of maintenance dredging were all predicted as a part of the analysis. Results from the aforementioned field and office studies were used to compute the shoaling rates.

102. Most empirical methods used to predict shoaling rates in offshore channels rely on dredging records or bathymetric surveys. Because hydrographic data for the BRDC is limited, and maintenance dredging has not been performed, other techniques for predicting infilling rates were examined. Shoaling rates predicted for nearby projects where hydrographic and dredging records were available, were used to place confidence limits on calculations for the BRDC.

103. An analytic approach for predicting shoaling rates in offshore channels has been documented by Galvin (1983) and is used in this study. The method is based on a comparison of the sediment transport potential before and after dredging. The expression derived to calculate the bypassing sediment transport ratio is:

$$\text{Transport ratio} = (d_1/d_2)^{5/2} \tag{7}$$

where

transport ratio = ratio of the sediment transport potential in the dredged channel with the sediment transport on the offshore bar before dredging

d_1 = controlling depth of the offshore bar

d_2 = design depth of the channel, including any overdredging

Using the transport ratio, and the estimated longshore drift rates, the amount of material trapped in the channel can be calculated using the following relationship:

$$\text{Shoaling rate} = RQ/CW\ [1 - \text{transport ratio}] \tag{8}$$

where

R = fraction of Q which occurs above d_2

Q = longshore transport rate

C = length of dredged channel

W = width of dredged channel

For this study, the shoaling rate (Equation 8) was modified to account for the fluvial load of the Brazos River. The resulting relationship is as follows:

$$\text{Shoaling rate} = \frac{RQ + FL}{CW} \left[1 - \text{transport rate}\right] \tag{9}$$

where FL is the volume of fluvial load deposited in the seaward 5,400 ft of channel. Major assumptions in the Galvin (1983) method are as follows:

- a. Sediment transport rate is proportional to the power supplied by waves to the surf zone
- b. The flow is turbulent, and friction coefficients are relatively low both before and after dredging
- c. Sediment is set in motion by wave-orbital velocities, and transported by currents.

104. Shoaling rates using the Galvin (1983) method were calculated for the seaward 5,400 ft of channel. Advance dredging depths of 2, 4, 6, and 8 ft were evaluated. Annual maintenance dredging requirements were calculated using a gross longshore transport estimate of 300,000 cu yd/year, and a fluvial deposition rate of 72,000 cu yd/year. A summary of these calculations is shown in Table 15. The results show that it would take approximately 0.87 year for the channel dredged to 20 ft to infill to the project depth of 12 ft. The proposed advance maintenance of 6 ft would require dredging three times each year in order to maintain the project depth.

Table 15

Estimated Annual Maintenance Dredging Requirements in the Seaward Portion of the Channel for 12-ft Project Depth with Advance Maintenance Dredging

Dredged Depth ft	Advance Maintenance ft	Length of Channel in Open Gulf ft	Project Duration year	Estimate Annual Maintenance cu yd
12	0	2,900	0	362,700
14	2	3,500	0.09	365,700
16	4	4,300	0.22	367,500
18	6	5,400	0.41	368,700
20	8	8,500	0.87	369,400

105. The estimated annual maintenance requirements shown in Table 15, which are associated with the greater advance maintenance may represent maximum values. As the channel upstream is dredged to greater depths, less fluvial sediment is available for deposition in the offshore portion of the channel. For this study, the exact decrease in fluvial sediment supply could not be calculated, and a constant 72,000 cu yd was used for all advance maintenance depths.

106. The dredging requirements given in Table 15 are based on channel lengths in the open Gulf extending to offshore depths equal to the advance maintenance depths evaluated. Because offshore slopes in the vicinity of the BRDC are extremely gentle (1:700), the design channels extend for considerable distances offshore. As a possible solution, CERC was asked to evaluate shoaling rates based on advance maintenance to the 12-ft contour with side and end channel slopes of 1:6. Similar slopes are used on the offshore channel at Freeport Harbor, although the stability at the BRDC is unknown because of the finer grain sizes present. Channel lengths and project duration were calculated for advance maintenance to the 12-ft contour, and are summarized in Table 16. Significant reductions in channel length and project duration result from these design considerations. For the proposed 12-ft project with 6-ft advance maintenance, dredging would be required every 0.2 year in order to maintain the project depth. Annual maintenance requirements would also increase with a shorter channel, although the exact volumes could not be calculated for this study.

Table 16

Estimated Project Duration for Advance Maintenance Dredging to 12-ft Depth Contour

Dredged Depth ft	Advance Maintenance to 12-ft Contour, ft	Length of Channel in Open Gulf ft	Project Duration, yr
12	0	2,900	0.0
14	2	2,912	0.07
16	4	2,924	0.15
18	6	2,936	0.22
20	8	2,948	0.30

107. Table 17 illustrates annual maintenance requirements for the entire length of the channel, as determined from a summation of estimates for the upstream and offshore sections of the channel. Values range from 623,700 to 784,800 cu yd. These volumes compare favorably with an average dredging rate of 860,000 cu yd/year calculated for Freeport Harbor by Mason (1981).

Table 17

Estimated Annual Maintenance Dredging for Design Channel

Advance Maintenance ft	Total Dredged Depth, ft	Estimated Annual Maintenance in Channel cu yd/year	Estimated Annual Maintenance in Offshore Bar cu yd/year	Estimated Annual Maintenance in Design Channel cu yd/year
0	12	261,000	362,700	623,700
2	14	295,000	365,700	660,700
4	16	329,000	367,500	696,500
6	18	366,000	368,700	734,700
8	20	415,000	369,400	784,400

PART VI: DISCUSSION AND CONCLUSIONS

108. The preceding sections of this report have discussed the results of a combined analytic, numerical, and field study designed to estimate shoaling rates for the proposed navigation project at the BRDC. The following section will summarize these results in terms of evaluating the feasibility of dredging the BRDC.

Stability of the BRDC Delta

109. Analyses of shoreline change maps and considerations of sediment volume changes on the BRDC delta reveal a two stage development. The first stage lasted approximately 19 years (1929 through 1948) and was marked by a rapid growth of both subaqueous and subaerial deposits. High total-water discharge and suspended sediment concentrations reported for the Brazos River during this stage were primarily responsible for the rapid growth of the delta. The existing waves and longshore currents were not capable of transporting the large quantities of sediment deposited at the mouth of the diversion. The dominance of fluvial processes during this first stage is supported by the triangular shape and extensive seaward progradation of the delta during this early stage information. The second stage of delta development lasted approximately 36 years (1949 through 1985) and can be characterized by a much slower rate of delta growth and a landward retreat of the delta. These changes were the result of a decrease in both high discharge events and sediment availability. The reductions were brought on by dam and reservoir construction within the Brazos River drainage basin. Within the past 28 years (1957 through 1985), the most significant change in the BRDC delta has been a redistribution of sediments to the west, resulting from the predominant net-westerly longshore transport. This recent stability of the BRDC delta suggests that a balance has been achieved between the fluvial and Gulf processes responsible for sediment transport. Barring any major changes in sediment supply, the morphology of the BRDC delta can be expected to remain relatively stable, with only minor redistributions of sediments to the west.

Sediment Transport

110. As concluded by this study and other studies on littoral

transport, the direction of net longshore transport in the vicinity of the BRDC is to the west. Yearly average net longshore transport is between 40,000 and 60,000 cu yd. Seasonal littoral transport rates are characterized by a westerly dominance from October to April, with an easterly reversal during the rest of the year. Annual gross longshore-transport values range from 175,000 cu yd with an average of 300,000 cu yd.

111. Considerations of the hydraulics of the lower BRDC indicate that sediment transport into the Gulf of Mexico occurs on a seasonal basis. During the times of the year when riverine sediment loading exceeds the transport capacity, sediment is deposited along the diversion and entrance channels. During the times when the riverine sediment loading is less than the transport capacity, sediment is scoured from these channels. Because of the limited bathymetric data from the lower BRDC, determinations could not be made on the duration of the shoaling and erosion cycle within the channel. Detailed information of this type is necessary to accurately determine annual shoaling rates.

Shoaling Rates

112. Based on the bathymetric surveys taken in August 1982 and December 1984, the shoaled material in the lower BRDC channel and offshore portion of the channel totaled approximately 330,000 cu yd. Seventy-eight percent or 261,000 cu yd of sediment were deposited in the channel between the floodgates and the Gulf, and 22 percent or 72,000 cu yd were deposited in the offshore portion of the channel. The feasibility of dredging the proposed channel was evaluated based on these annual shoaling rates of 261,000 and 72,000 cu yd. For the basic 12-ft-deep by 125-ft-wide channel, with 6-ft overdredging, the annual maintenance dredging requirements for the part of the channel between the floodgates and the Gulf was estimated at 366,000 cu yd (Table 13). Annual maintenance dredging requirements for the seaward 5,400 ft of channel were estimated at 368,700 cu yd (Table 15). Total maintenance dredging requirements for the proposed BRDC project were estimated at 734,700 cu yd annually (Table 17). The predicted shoaling rates indicate that the proposed channel could shoal to the project depth of 12 ft in approximately 4 months, thus requiring frequent maintenance dredging if the project is to be fully maintained throughout the year.

Additional Maintenance Considerations

113. Upon request by SWG, CERC was asked to evaluate the feasibility of agitation dredging as a supplement to conventional dredging techniques. The effects of unintentional propwash agitation dredging on channel maintenance within the BRDC have been evaluated based on the volume of boat traffic currently using the diversion channel. This type of dredging is caused by agitation of boat propellers while moving through a channel, or freeing themselves after grounding, and is most effective where the combination of sediment size and currents results in transportation of the agitated material off the dredging site into deeper water. Table 18 reflects data provided by SWG regarding the type of vessel traffic presently using the diversion channel.

Table 18

Brazos River East Floodgate Traffic (Number of Trips)

Boat Type	Trips per Year	Draft, ft
Supply boats	850	12
	850	10
Crew boats	1,650	9
Utility boats	825	12
	825	10
Shrimp boats	625	6

114. An extensive survey of agitation dredging and the types of applications for which it is best suited has been published by Richardson (1984). The report concludes that propwash agitation dredging works best in moderate water depths (2 to 3 times the propwash vessel draft), using a vessel especially modified for the task. Based on the data in Table 18, the average vessel draft of 10 ft would be most effective in maintaining a channel dredged to 20 to 30 ft, rather than the proposed 12 ft. High removal rates of >200-300 cu yd/hr are possible with agitation dredging in shallow water; however, severe bottom scour may result, creating sediment ridges from the scoured material. Natural current velocities of 2-5 ft/sec are required in most cases to transport the agitated material away from the dredging site. The maximum ebb currents of 2 ft/sec recorded in the BRDC (Figures 10, 15, and 18) may

therefore not be capable of transporting the agitated material. Based on the above results, it is suggested that the use of unintentional propwash dredging will have little or no affect on annual maintenance dredging requirements in the BRDC.

Additional Considerations

115. It is recommended that successful implementation of the BRDC project would be increased by future field studies. These studies should address the shoaling within the lower BRDC in terms of identifying the diversion of the seasonal shoaling and erosion cycles, and quantifying the volume of annual shoaling. Detailed knowledge of these processes would aid in determining optimum maintenance dredging times, and ensure maximum project duration. The feasibility of constructing jetties to reduce the frequency of dredging and to provide safe passage for vessels should also be evaluated.

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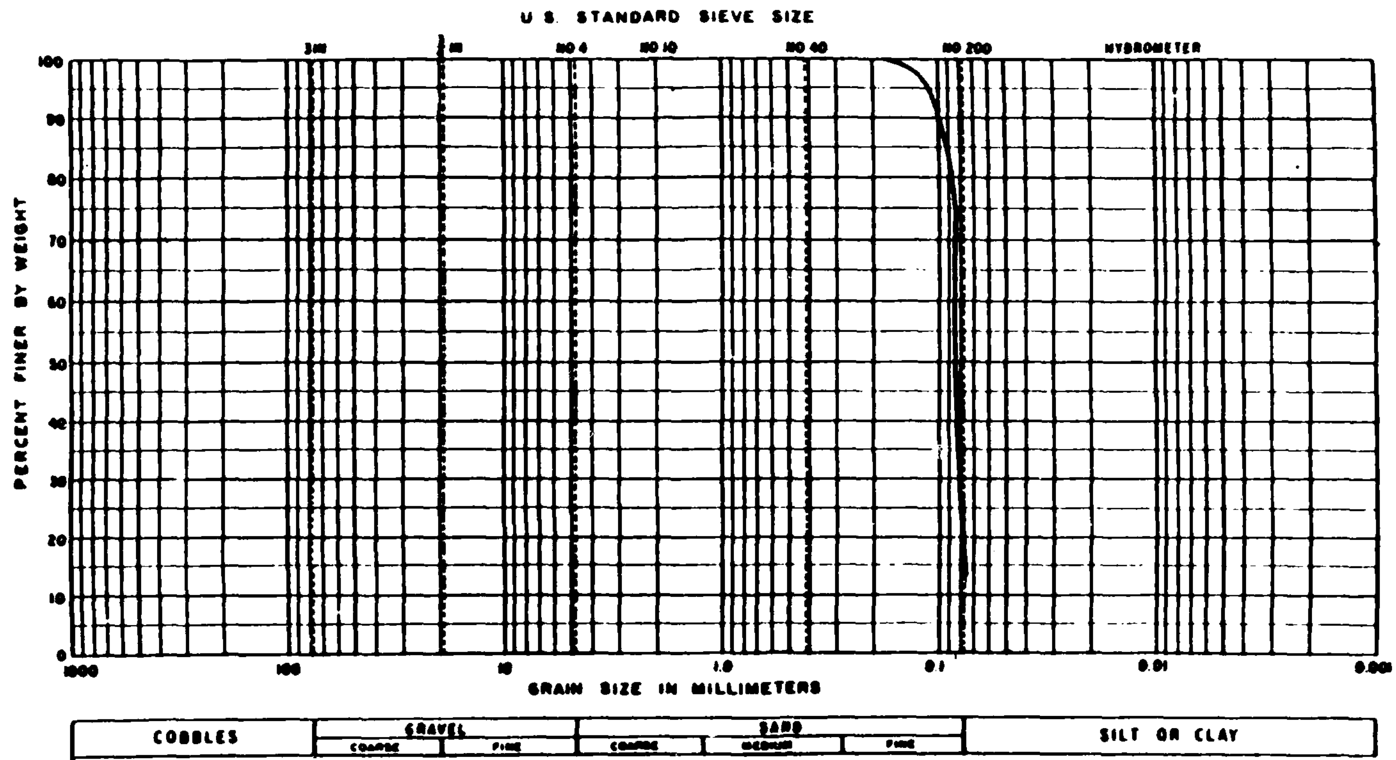
APPENDIX A: CUMULATIVE FREQUENCY PLOT OF GRAB SAMPLES COLLECTED FROM BRDC AND OFFSHORE DELTA



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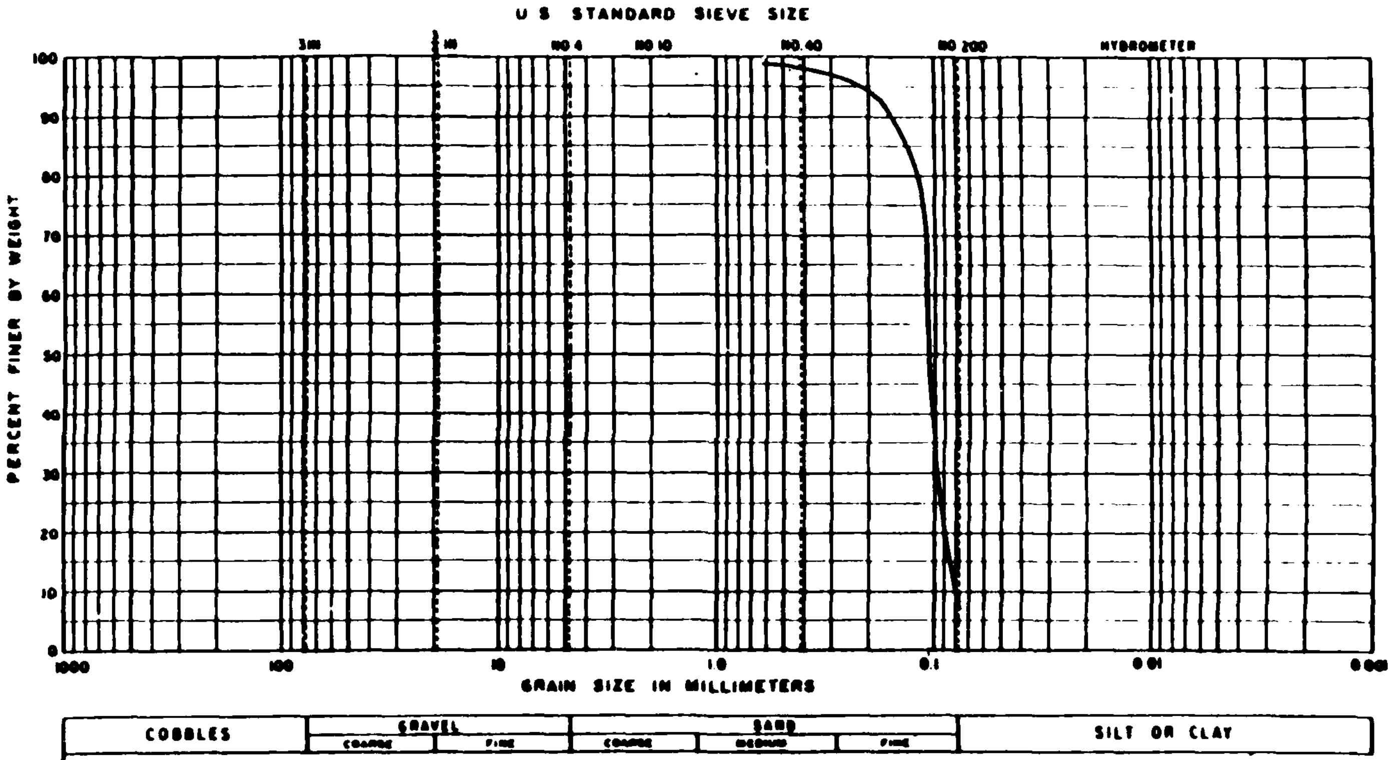
GRADATION CURVES



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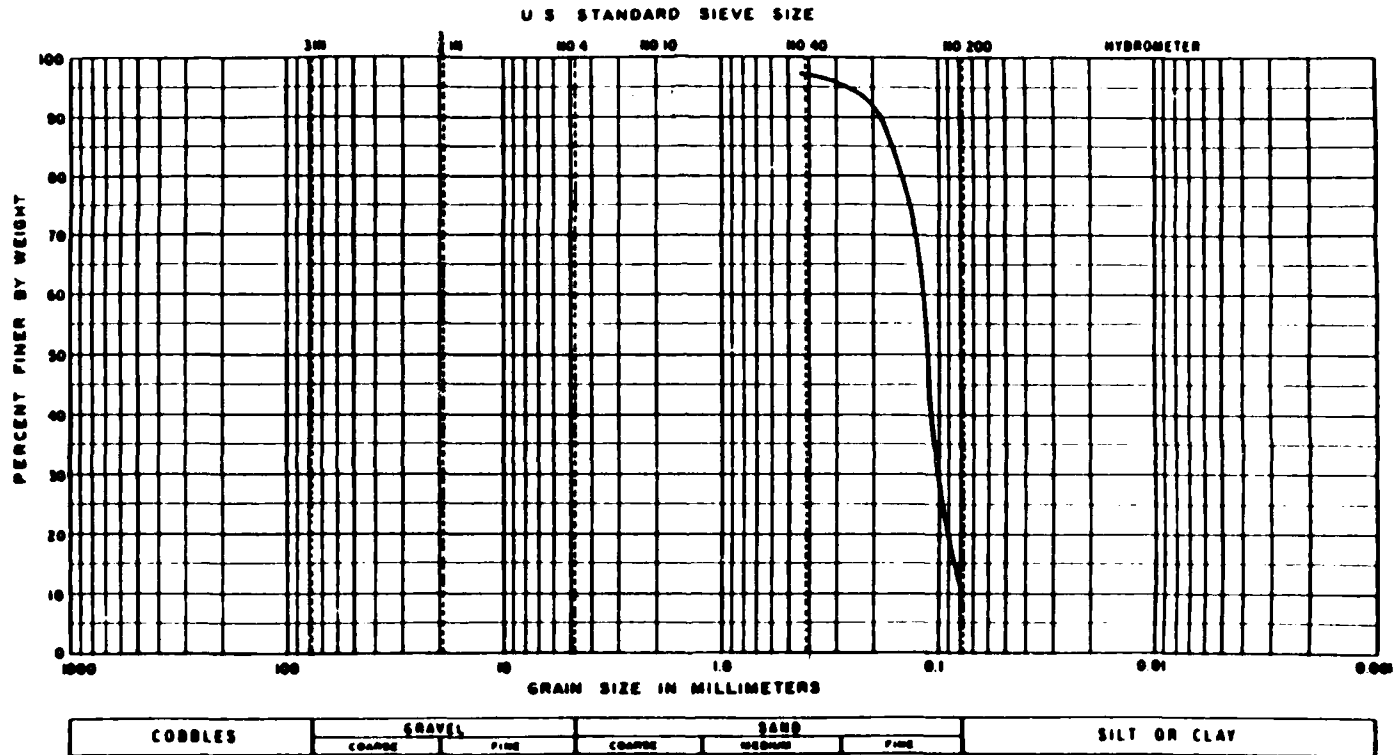

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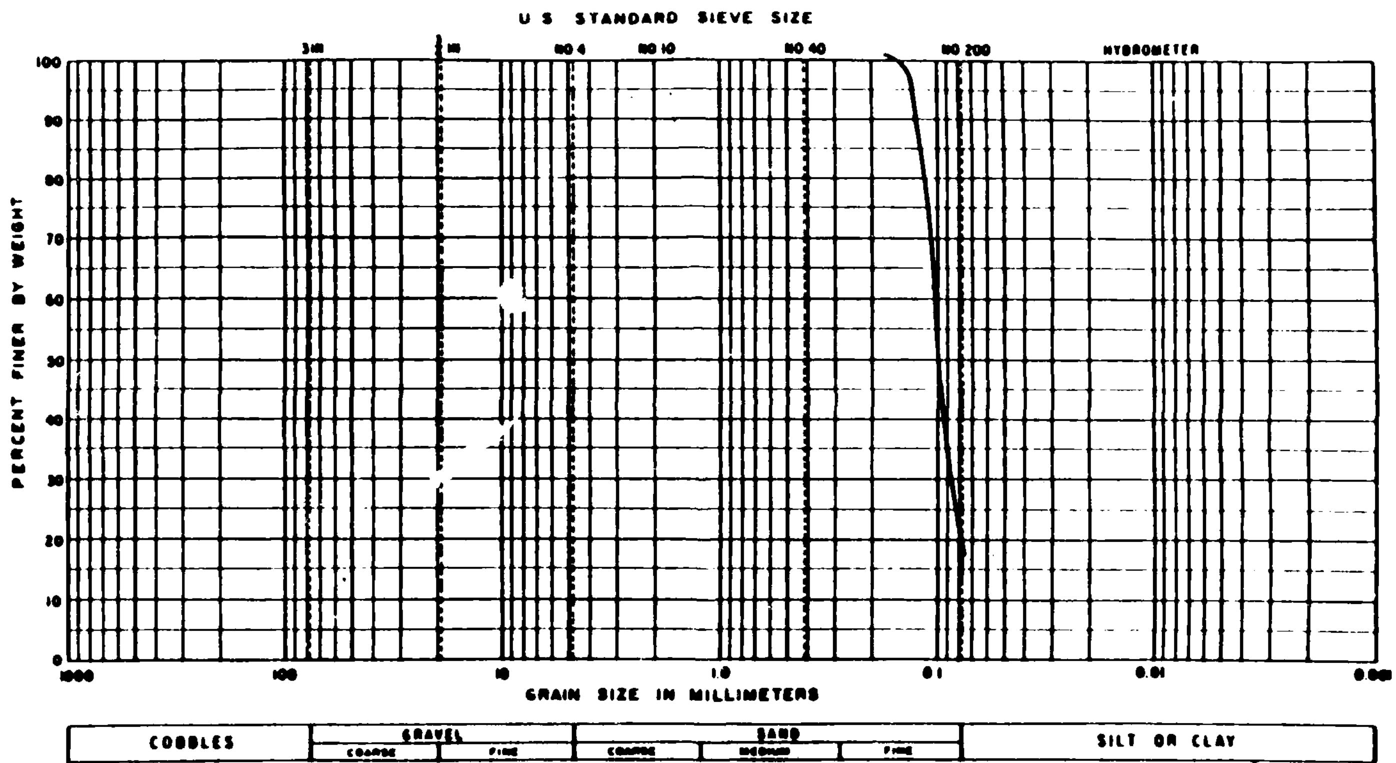
GRADATION CURVES



SAMPLE	ELEV-DEPTH	CLASSIFICATION	NAT WC	LL	PL	PI	
I-4		SM					

GRADATION CURVES

AD-A193 979 ANALYSIS OF SEDIMENT TRANSPORT IN THE BRAZOS RIVER DIVERSION CHANNEL ENTRANCE REGION(U) COASTAL ENGINEERING RESEARCH CENTER VICKSBURG MS 2/2

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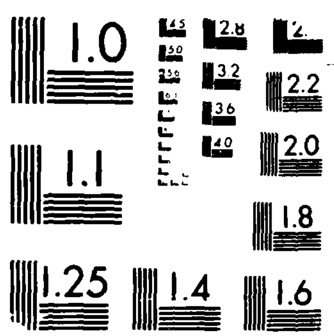
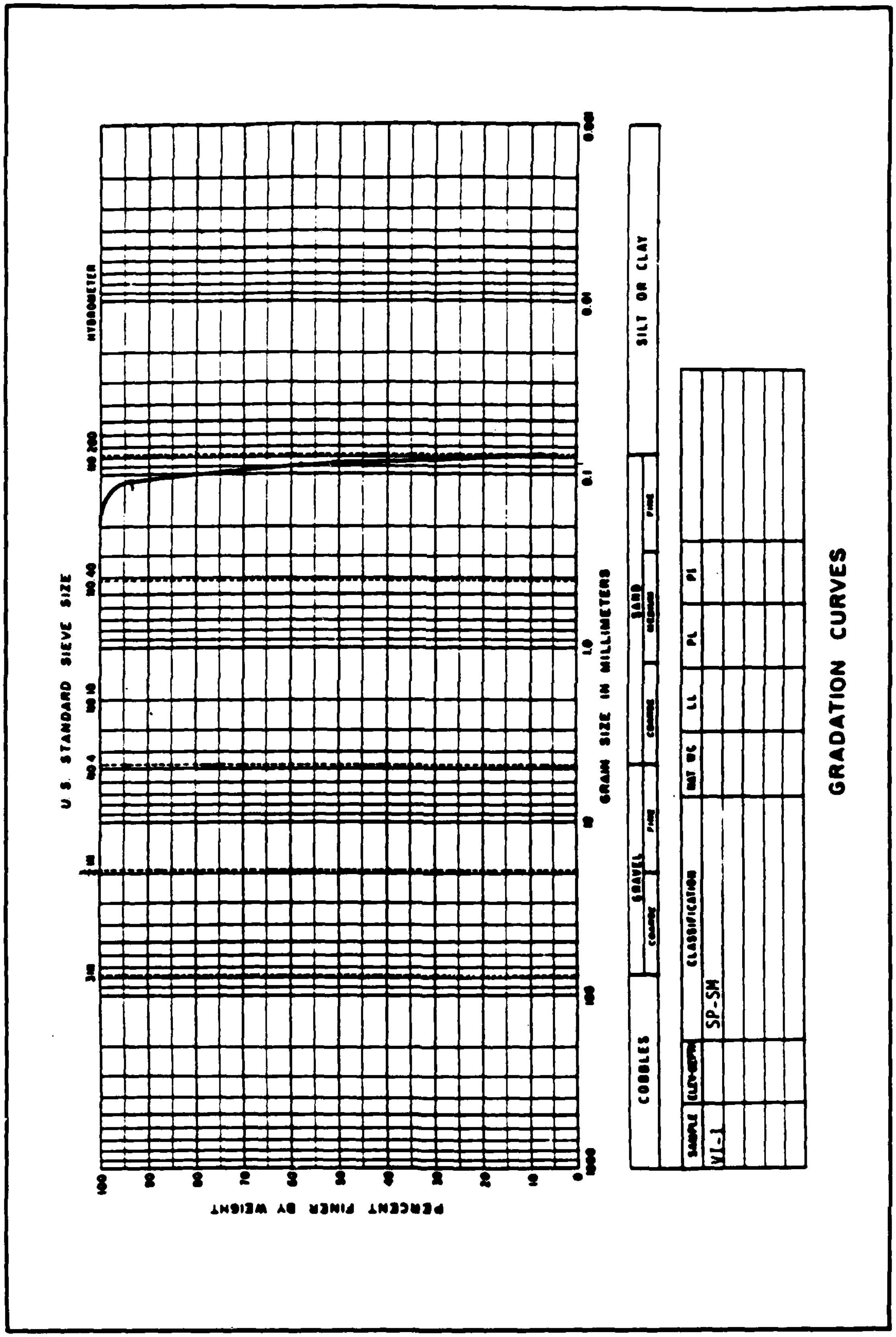


MICROCOPY RESOLUTION TEST CHART

STANDARDS 1963 A


U.S. STANDARD SIEVE SIZE
HYDROMETER
GRAIN SIZE IN MILLIMETERS
1000
100
10
1.0
0.1
0.01
0.001
PERCENT FINER BY WEIGHT
100
90
80
70
60
50
40
30
20
10
0
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
SAMPLE
ELEV-DEPTH
CLASSIFICATION
NAT WC
LL
PL
PI
VT-1
SP-SM
GRADATION CURVES

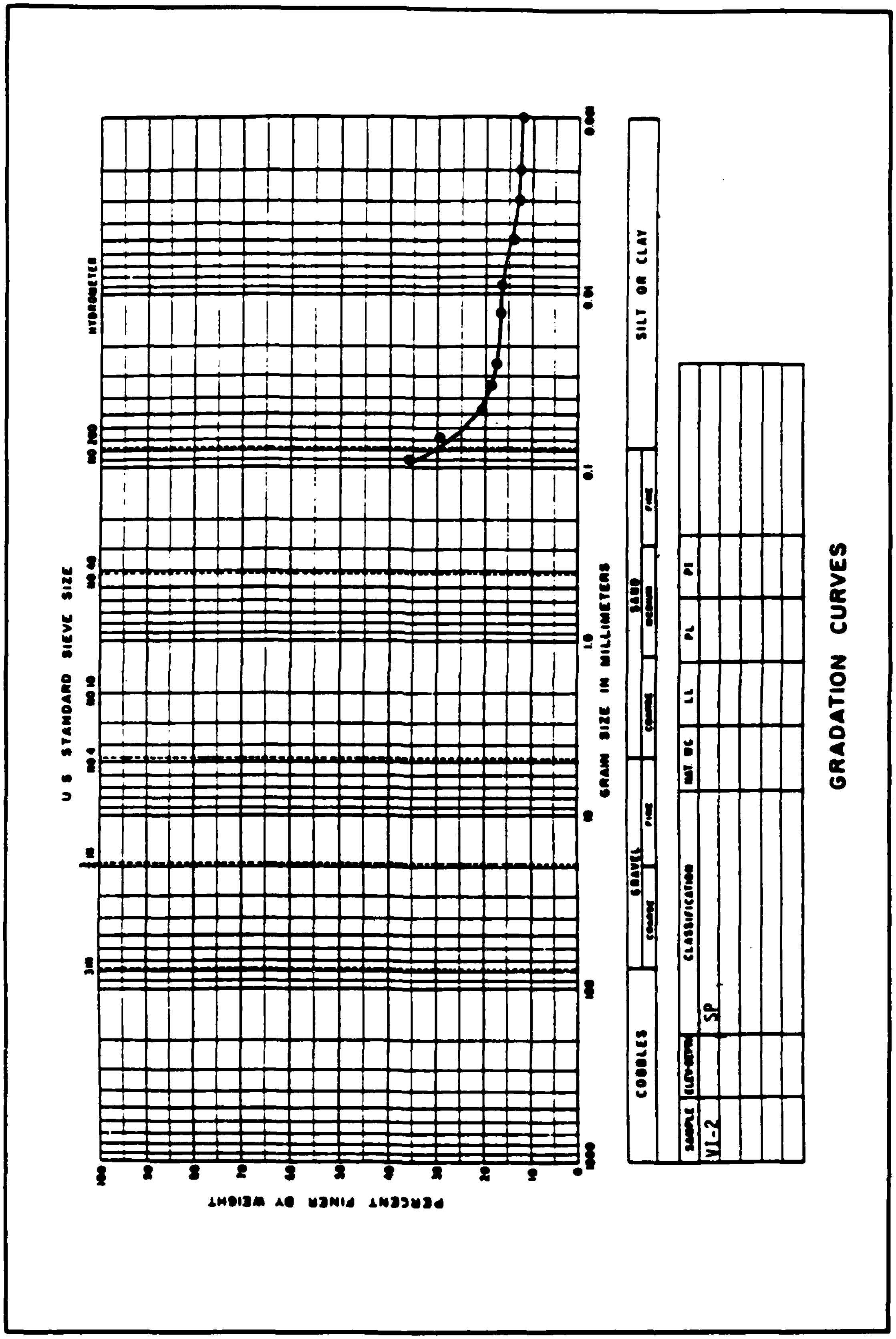
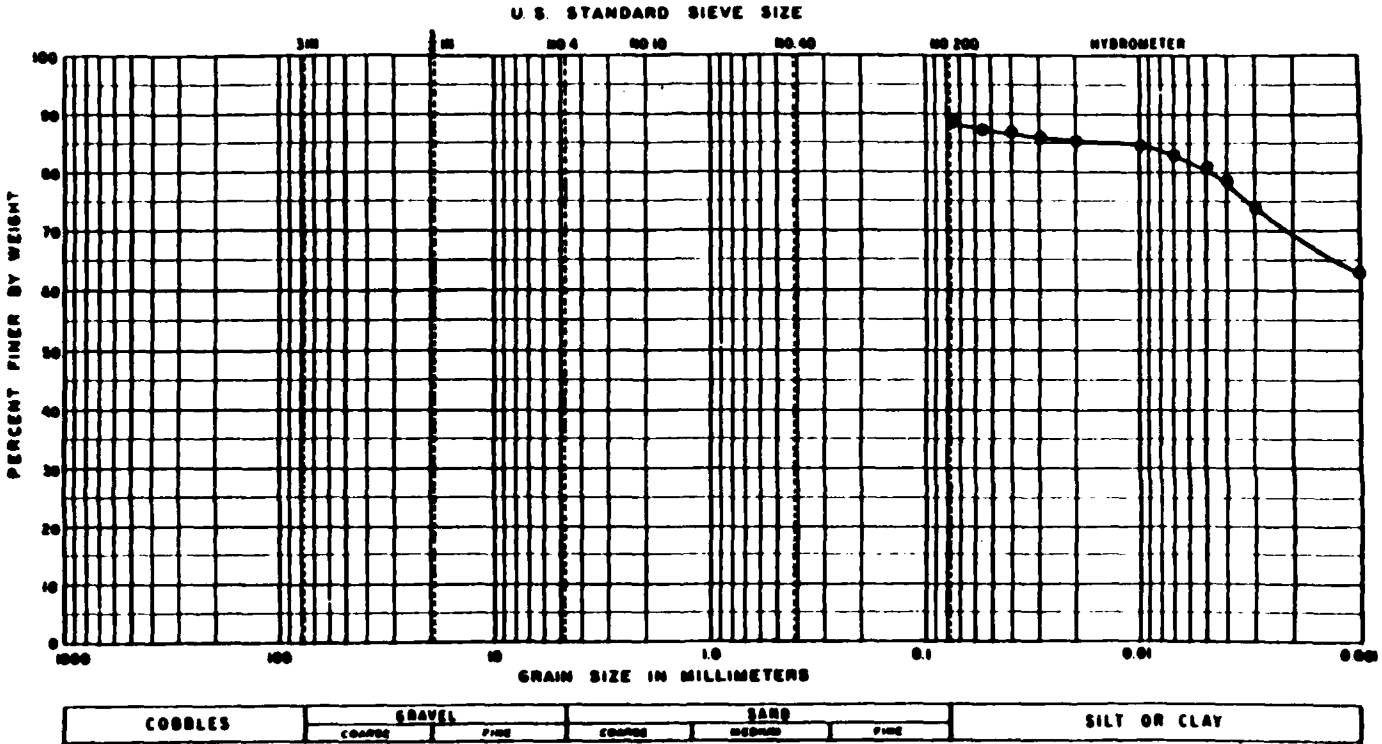
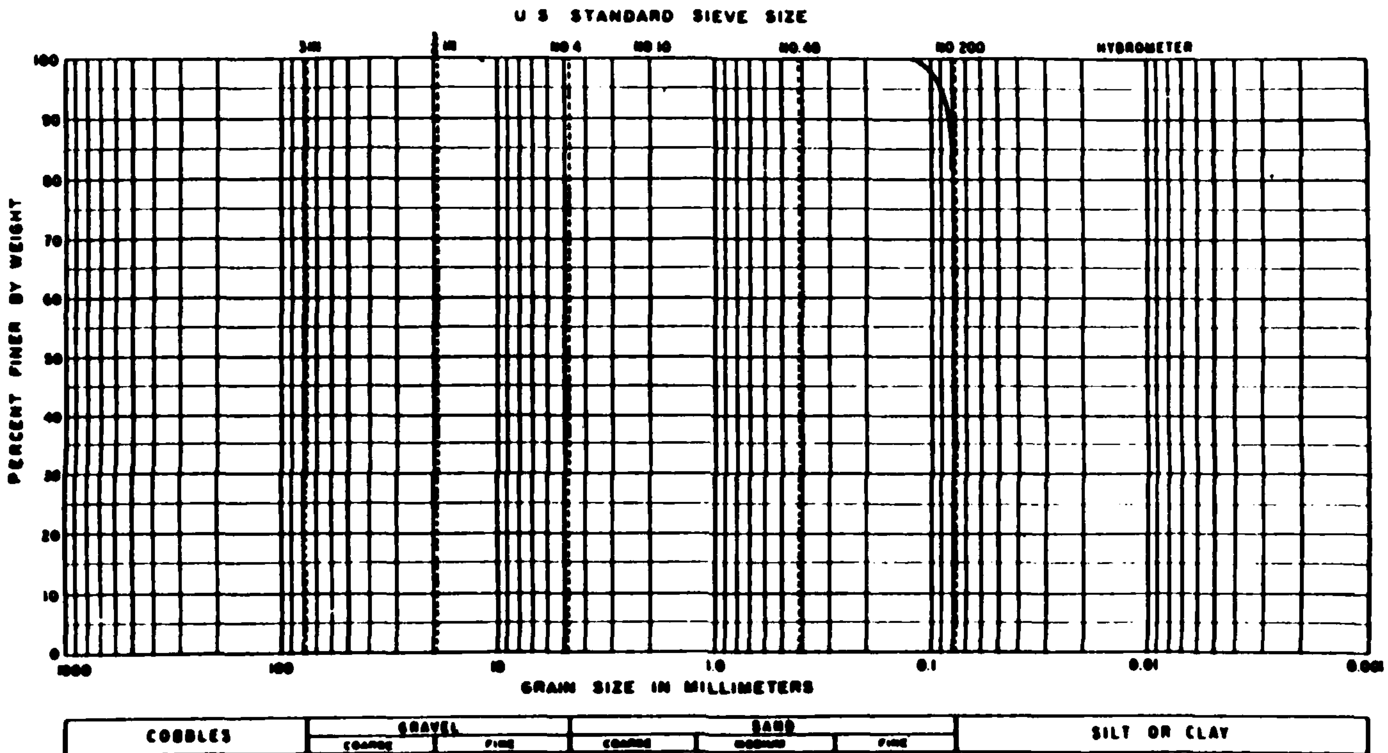

U S STANDARD SIEVE SIZE
HYDROMETER
GRAIN SIZE IN MILLIMETERS
PERCENT FINER BY WEIGHT
COBBLES
GRAVEL
SAND
SILT OR CLAY
SAMPLE
CLASSIFICATION
NAT WC
LL
PL
PI
VI-2
SP
GRADATION CURVES

PLATE A6



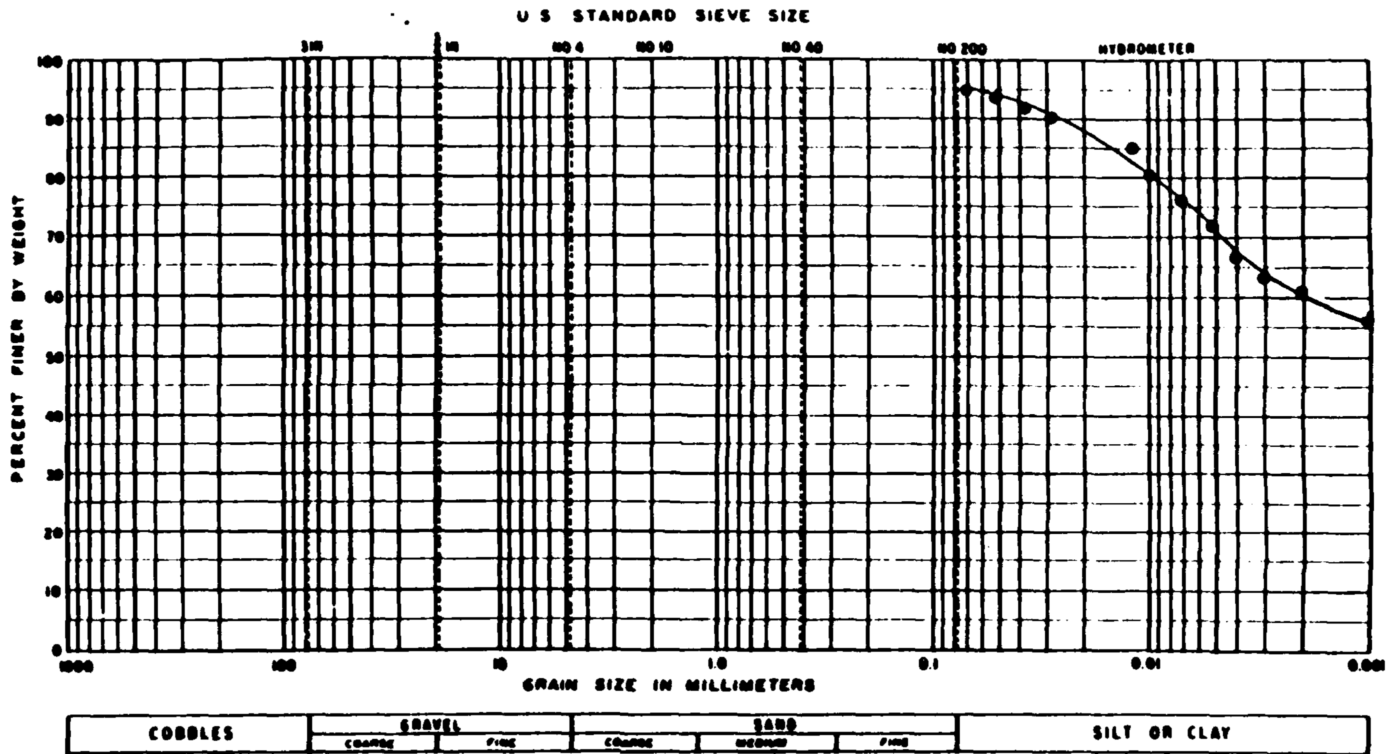
SAMPLE	ELEV-DEPTH	CLASSIFICATION	NAT WC	LL	PL	PI	
VI-3							

GRADATION CURVES



SAMPLE	ELEV-DEPTH	CLASSIFICATION	NAT WC	LL	PL	PI	
VI-3 (2 of 1)		ML					

GRADATION CURVES



SAMPLE	ELEV-DEPTH	CLASSIFICATION	NAT WC	LL	PL	PI	
VI-4							

GRADATION CURVES

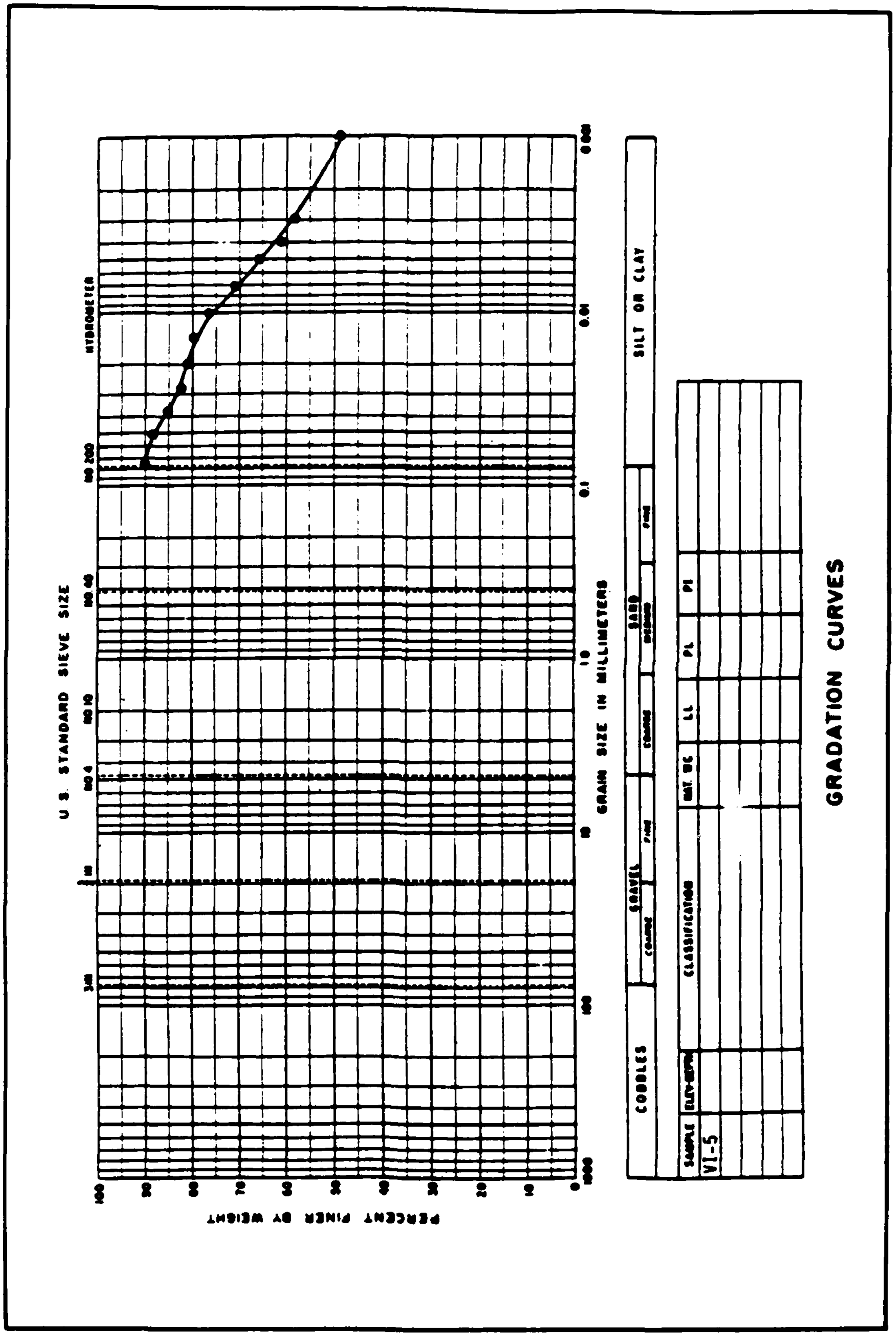
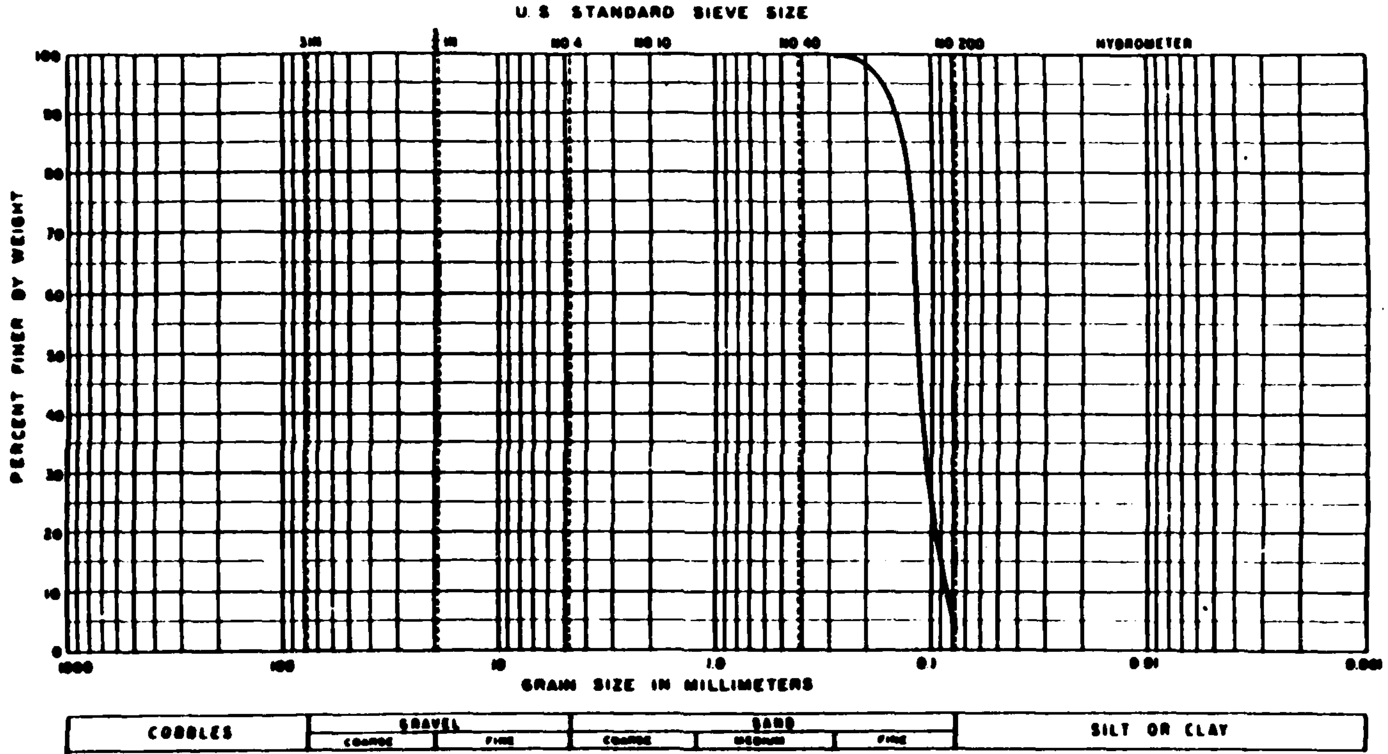
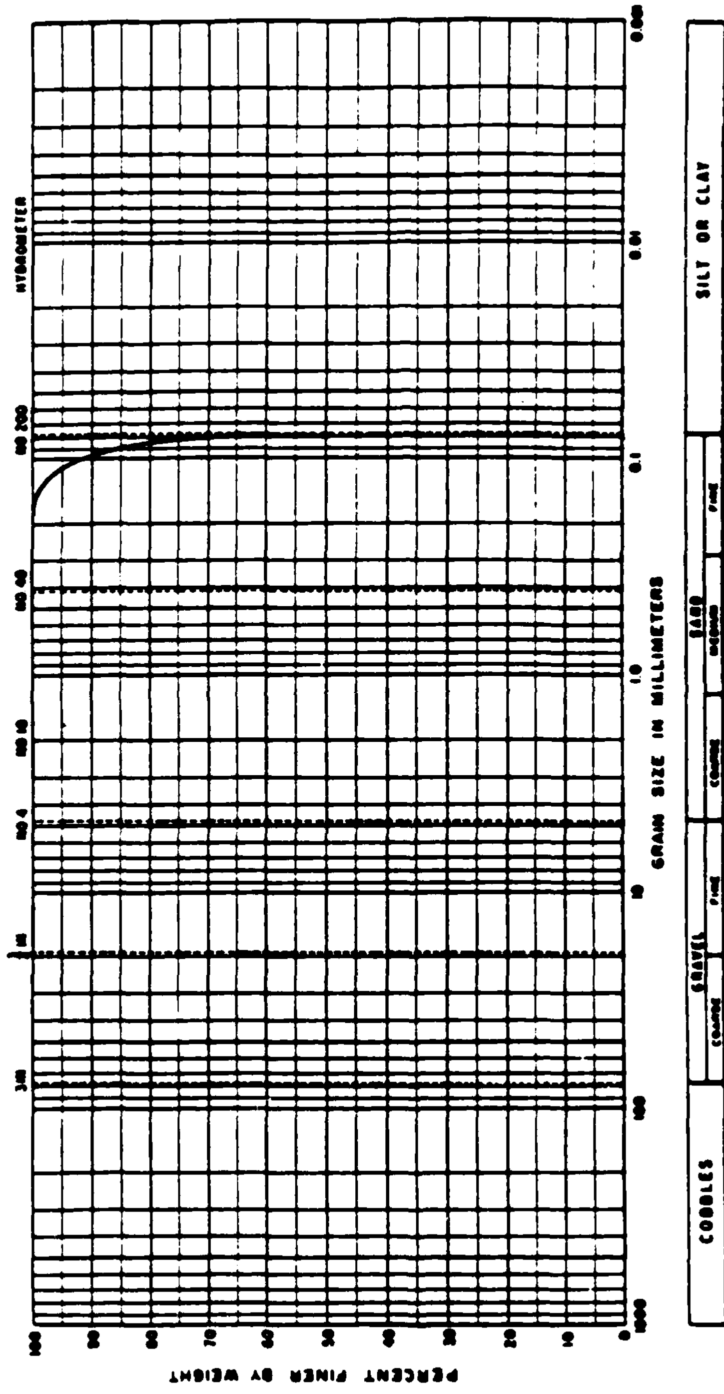

U.S. STANDARD SIEVE SIZE
HYDROMETER
NO 200
NO 40
NO 10
NO 4
3in
GRAIN SIZE IN MILLIMETERS
0.001
0.01
0.1
1.0
10
100
1000
PERCENT FINER BY WEIGHT
100
90
80
70
60
50
40
30
20
10
0
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
SAMPLE
ELEV-DEPTH
CLASSIFICATION
NAT. WC
LL
PL
PI
VI-5
GRADATION CURVES

PLATE A10



SAMPLE	ELEV-DEPTH	CLASSIFICATION	NAT WC	LL	PL	PI	
VII-1		SP					

GRADATION CURVES



SAMPLE	ELEV/DEPTH	CLASSIFICATION	NAT WC	LL	PL	PI
VII-2		SM				

GRADATION CURVES

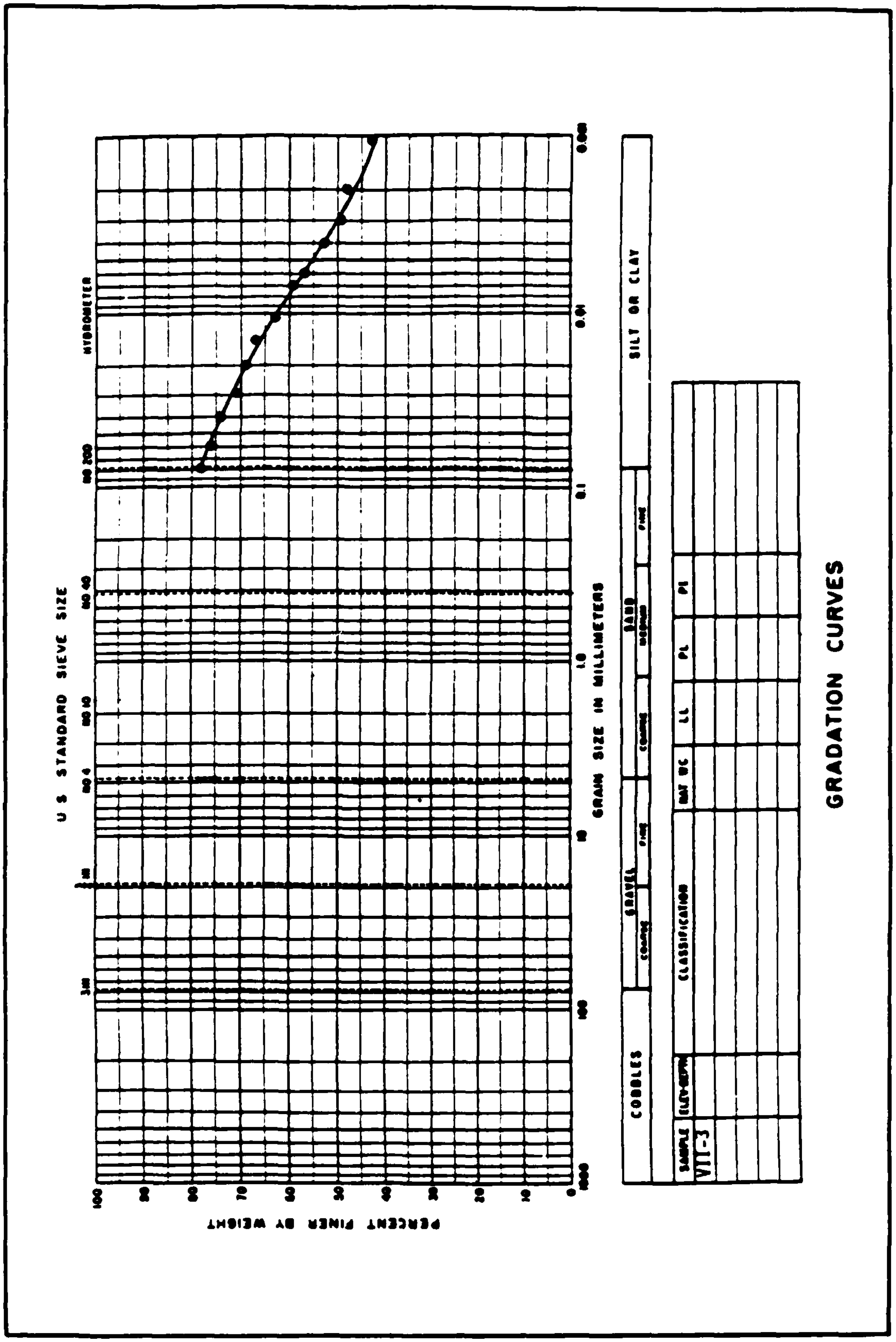
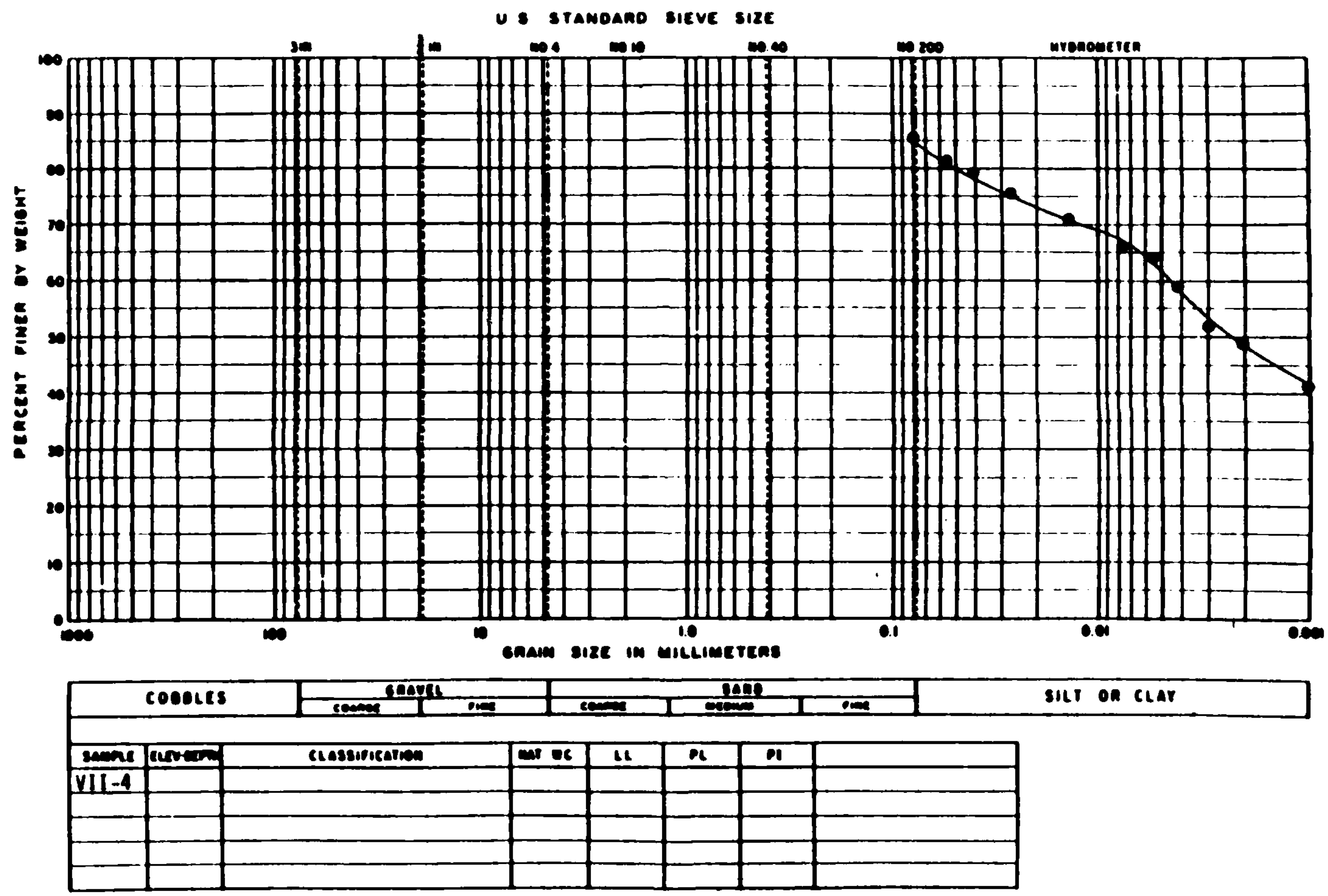
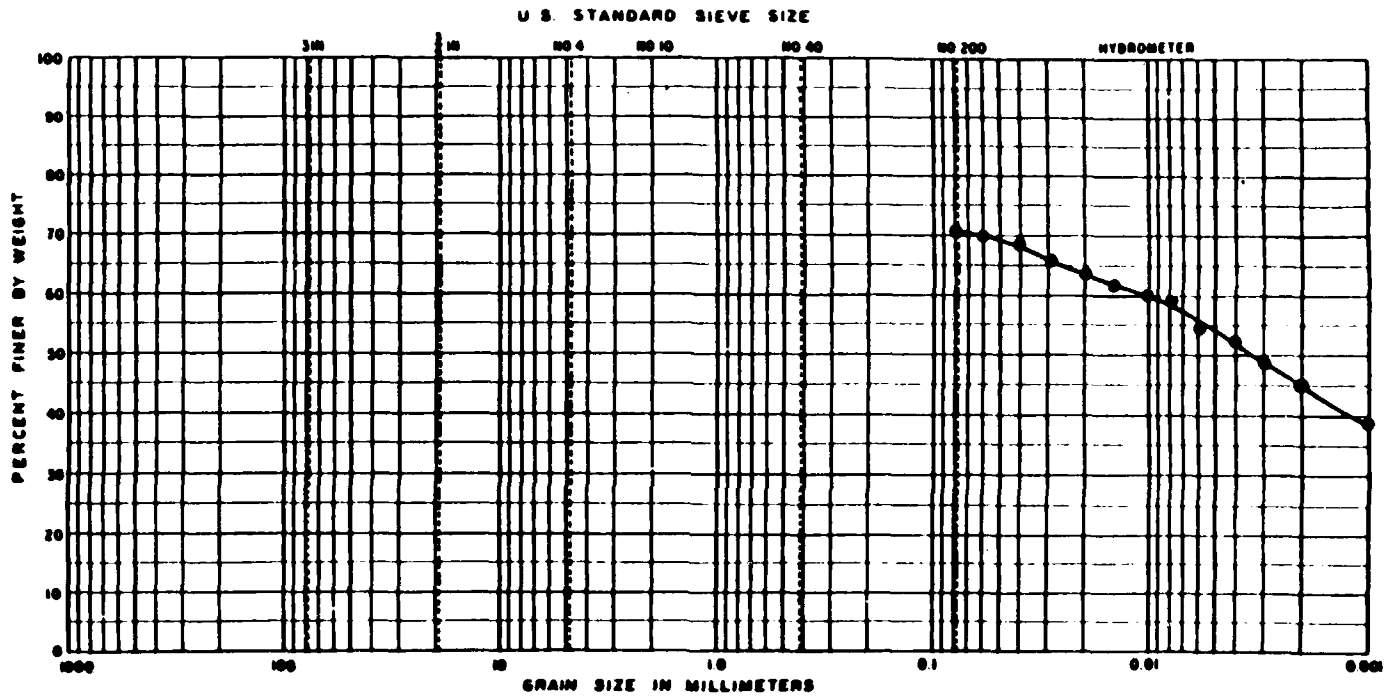

U S STANDARD SIEVE SIZE
HYDROMETER
PERCENT FINER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
COBBLES
GRAVEL
SAND
SILT OR CLAY
SAMPLE
CLASSIFICATION
NAT WC
LL
PL
PI
VII-3
GRADATION CURVES

PLATE A13



GRADATION CURVES

PLATE A14



COBBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	

SAMPLE	ELEV-DEPTH	CLASSIFICATION	NAT WC	LL	PL	PI	
VII-5							

GRADATION CURVES

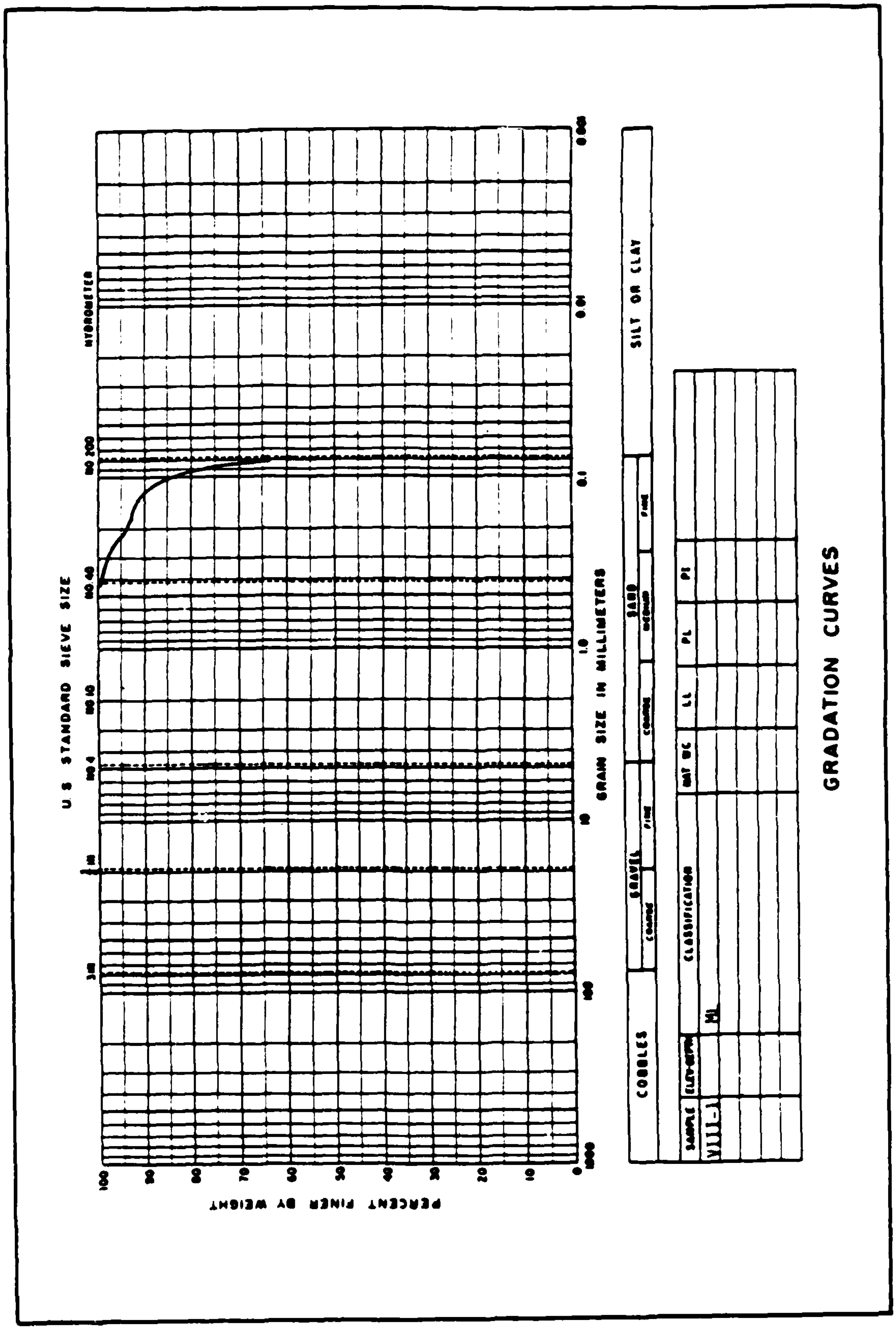

GRADATION CURVES
U S STANDARD SIEVE SIZE
HYDROMETER
GRAIN SIZE IN MILLIMETERS
PERCENT FINER BY WEIGHT
COBBLES
GRAVEL
SAND
SILT OR CLAY
SAMPLE
CLASSIFICATION
NAT WC
LL
PL
PI
VIII-1
ML

PLATE A16

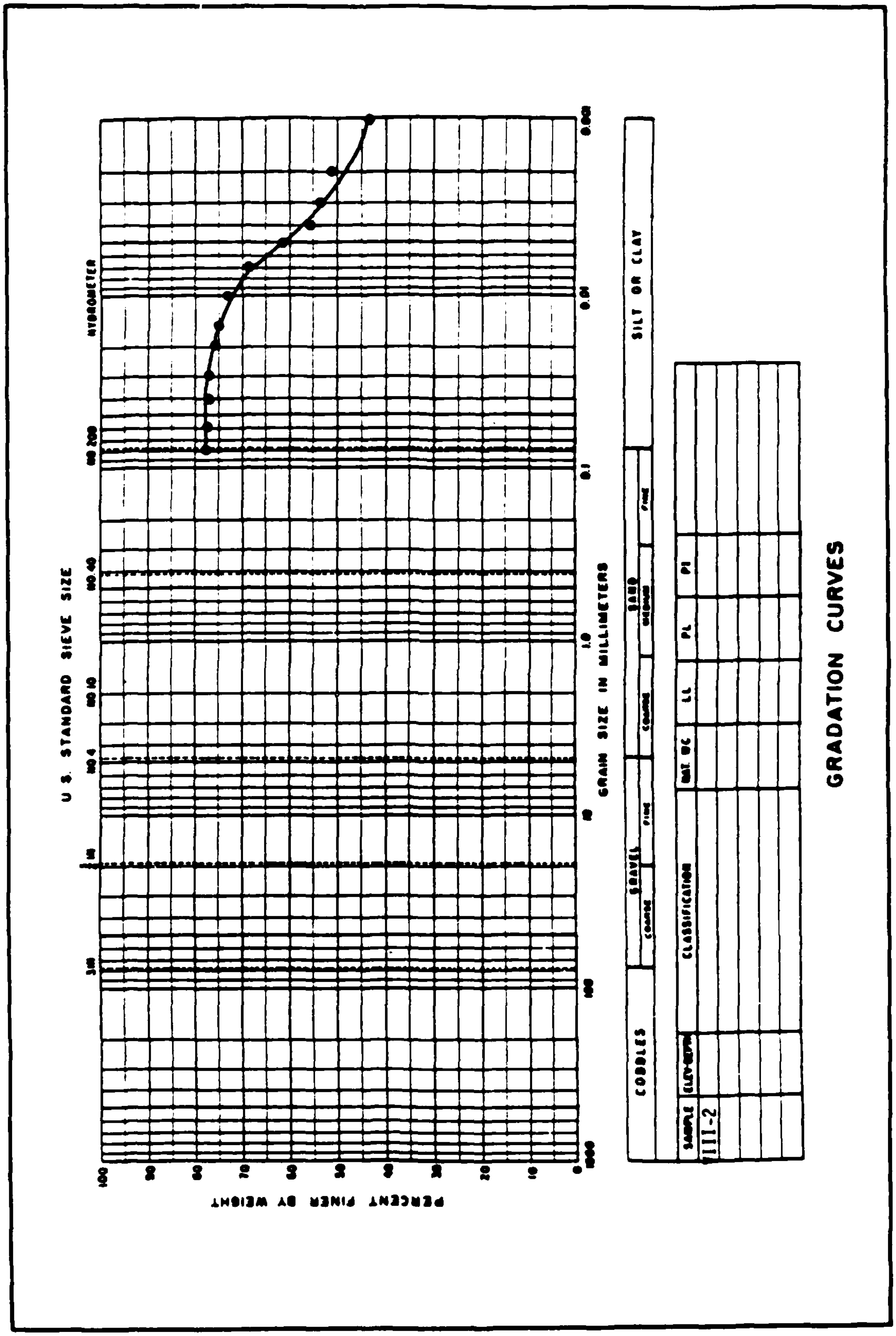

U.S. STANDARD SIEVE SIZE
HYDROMETER
GRAIN SIZE IN MILLIMETERS
PERCENT FINER BY WEIGHT
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
SAMPLE
ELEV/DEPTH
CLASSIFICATION
NAT WC
LL
PL
PI
III-2
GRADATION CURVES

PLATE A17

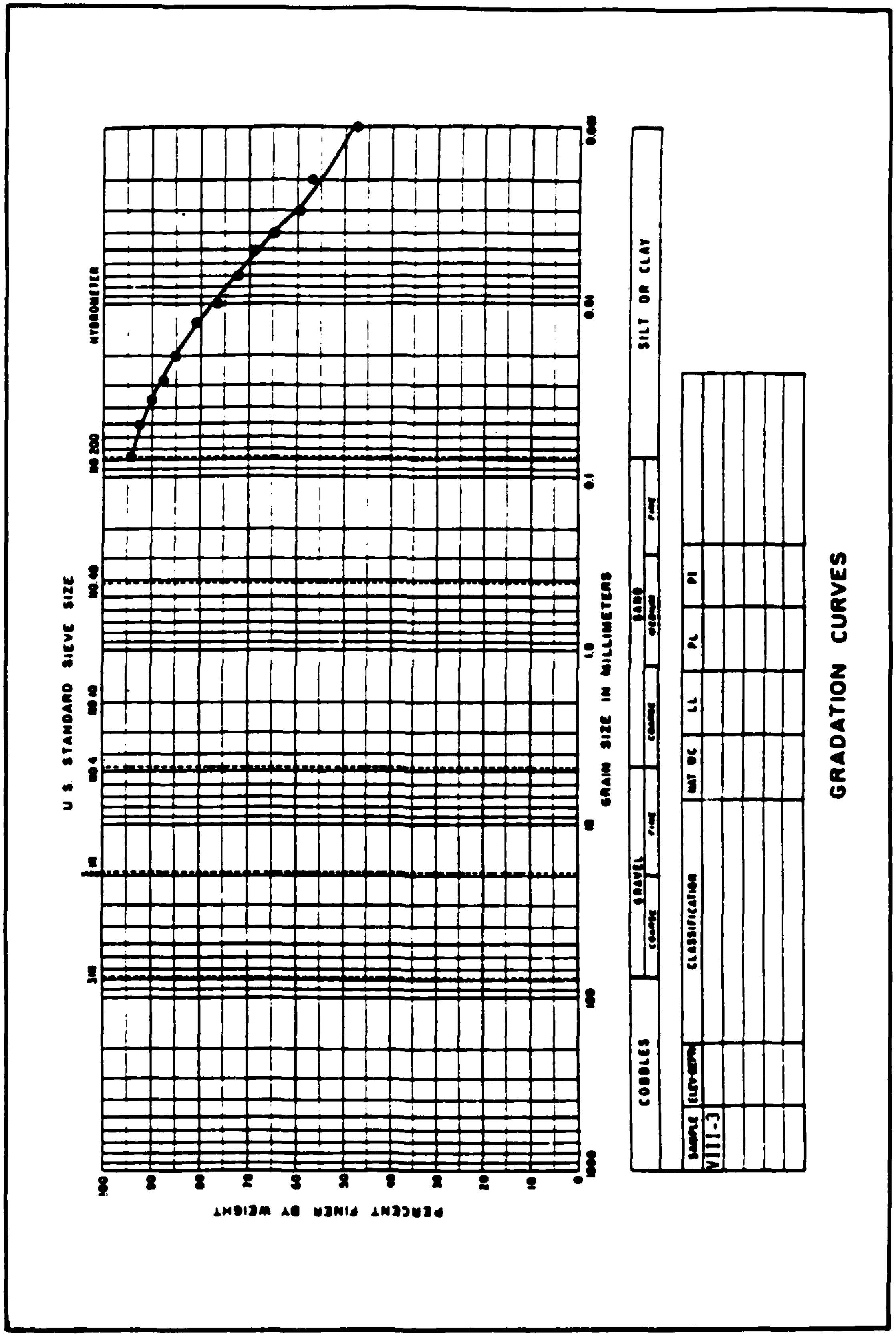
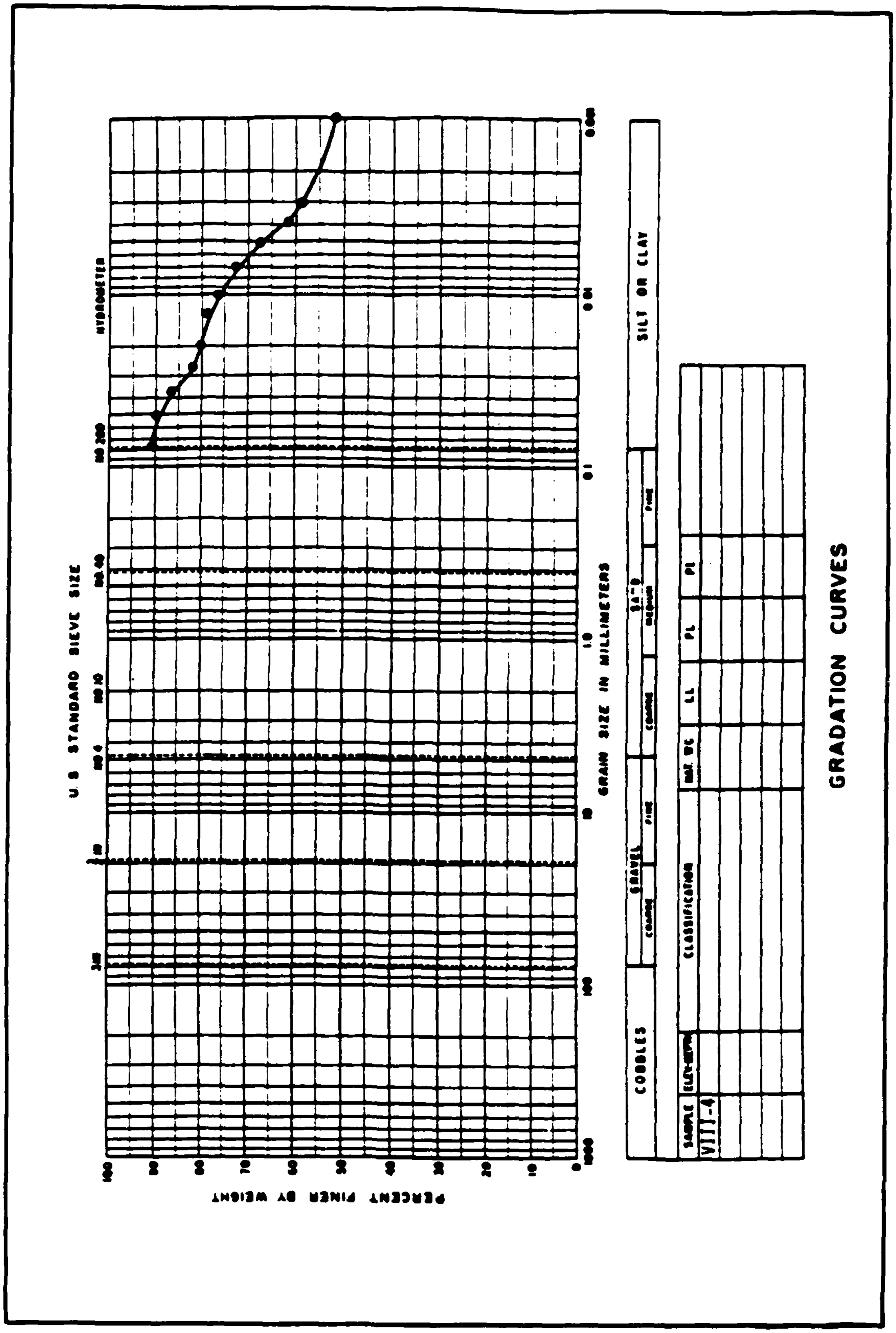
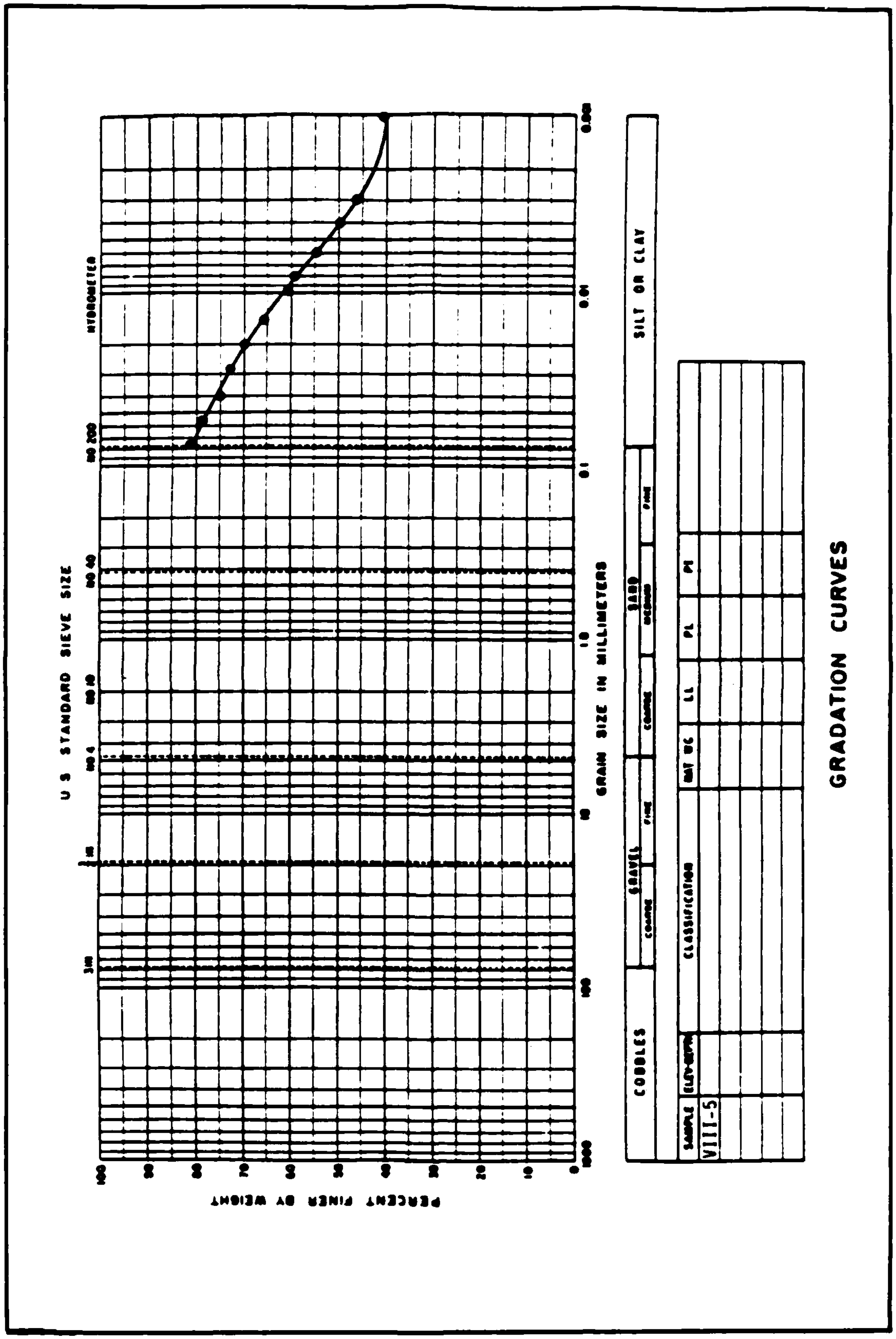
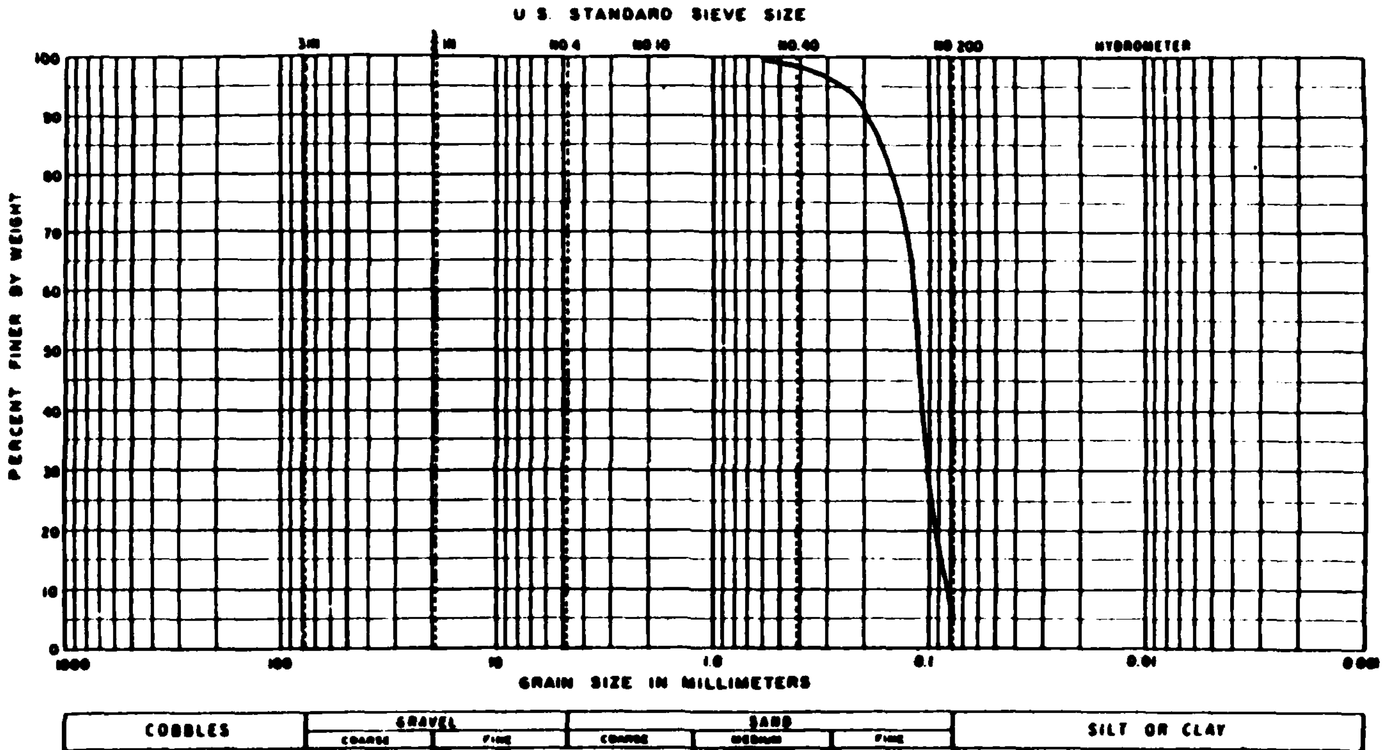

U S STANDARD SIEVE SIZE
HYDROMETER
GRAIN SIZE IN MILLIMETERS
0.001
0.01
0.1
1.0
10
100
1000
PERCENT FINER BY WEIGHT
100
90
80
70
60
50
40
30
20
10
0
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
SAMPLE
ELEV-DEPTH
CLASSIFICATION
NAT WC
LL
PL
PI
VIII-3
GRADATION CURVES

PLATE A18

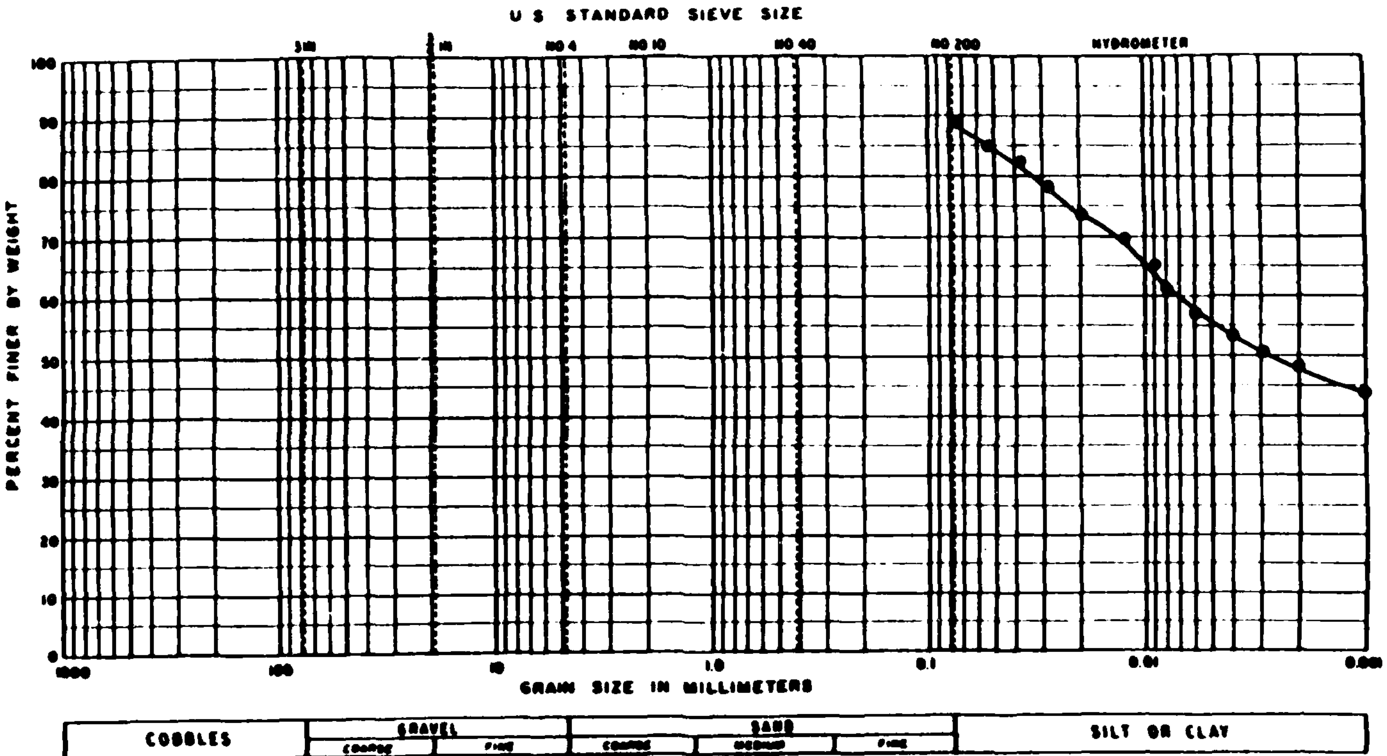

U.S. STANDARD SIEVE SIZE
HYDROMETER
PERCENT FINER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
SAMPLE
ELEV/DEPTH
CLASSIFICATION
NAT WC
LL
PL
PI
VIII-4
GRADATION CURVES


U S STANDARD SIEVE SIZE
HYDROMETER
PERCENT FINER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
SAMPLE
ELEV-DEPTH
CLASSIFICATION
NAT WC
LL
PL
PI
VIII-5
GRADATION CURVES



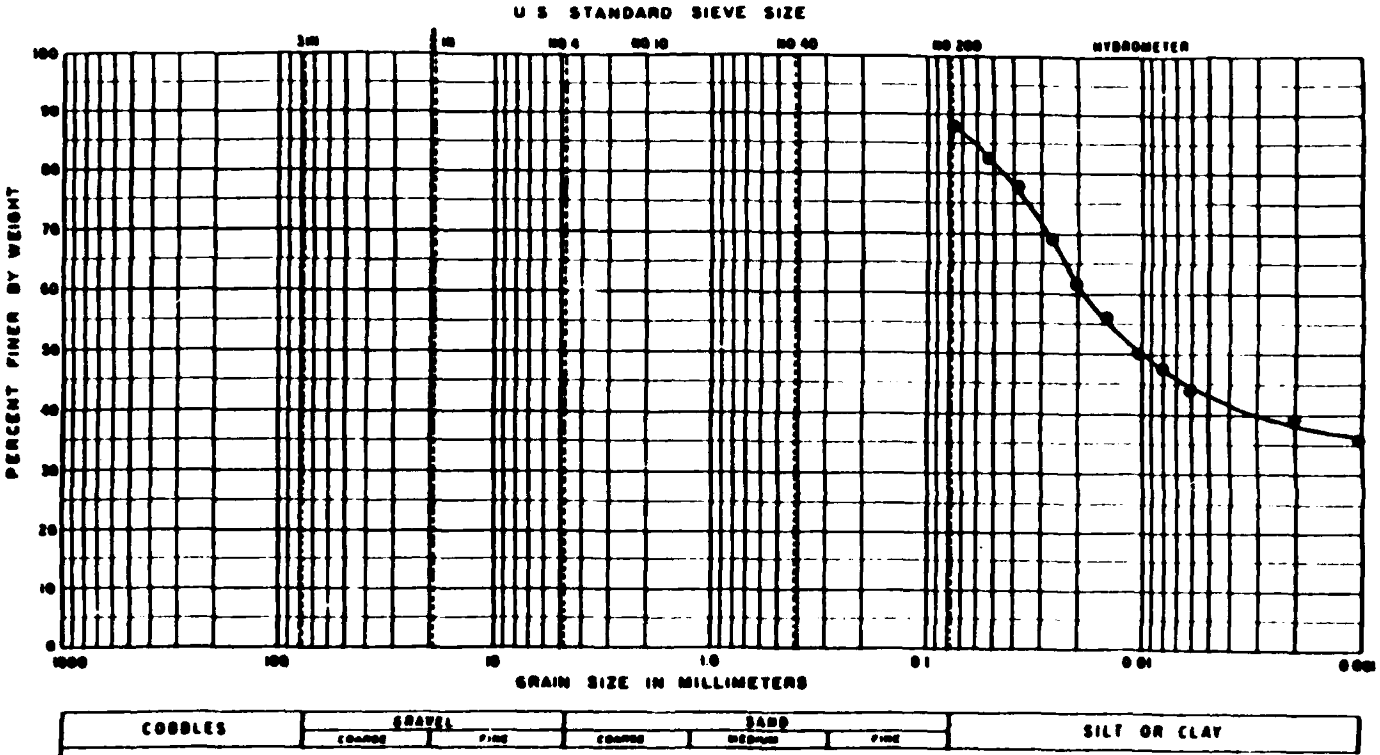
SAMPLE	ELEV-DEPTH	CLASSIFICATION	NAT WC	LL	PL	PI	
X-1		SP-SM					

GRADATION CURVES



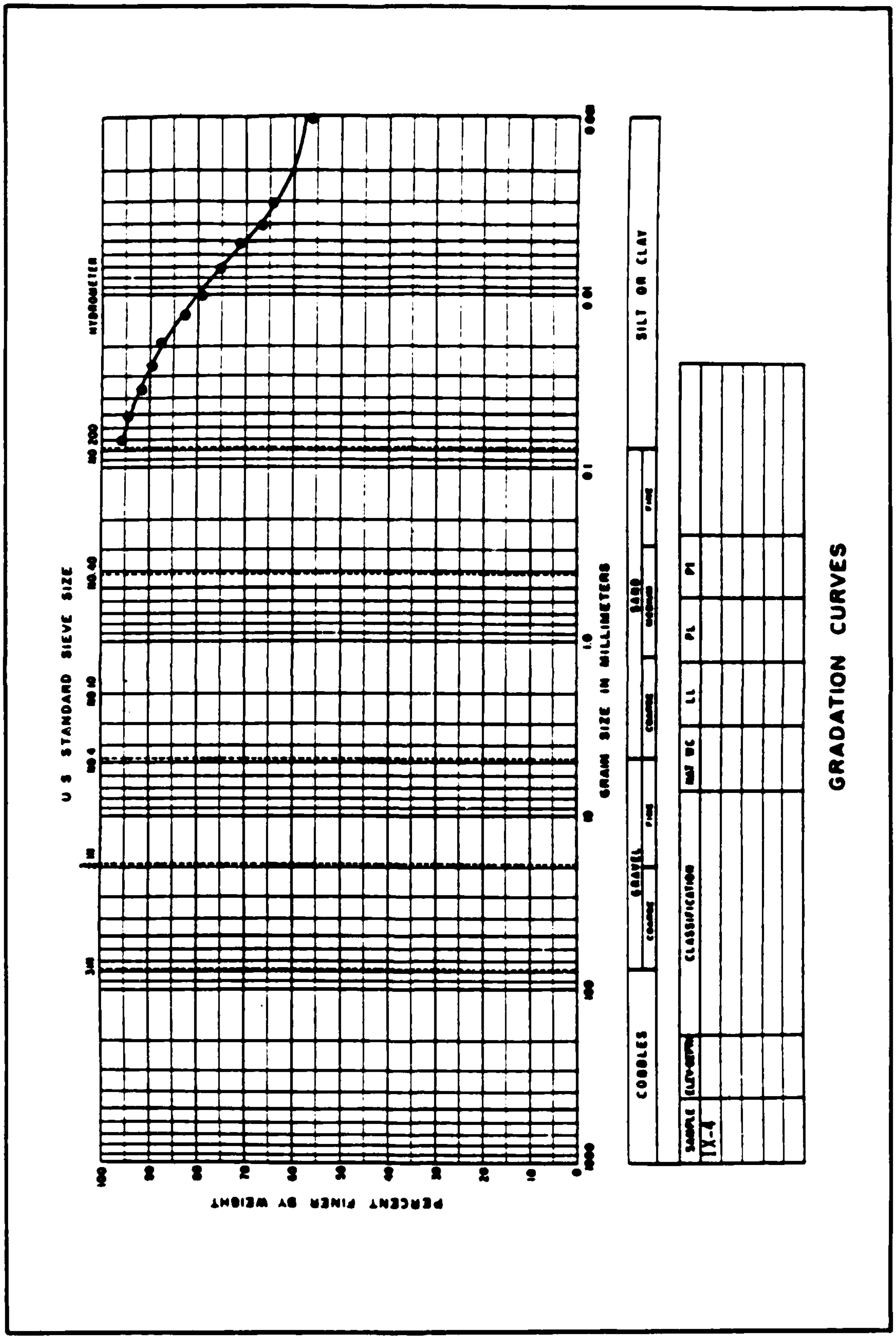
SAMPLE	ELEV-DEPTH	CLASSIFICATION	NAT WC	LL	PL	PI	
IX-2							

GRADATION CURVES



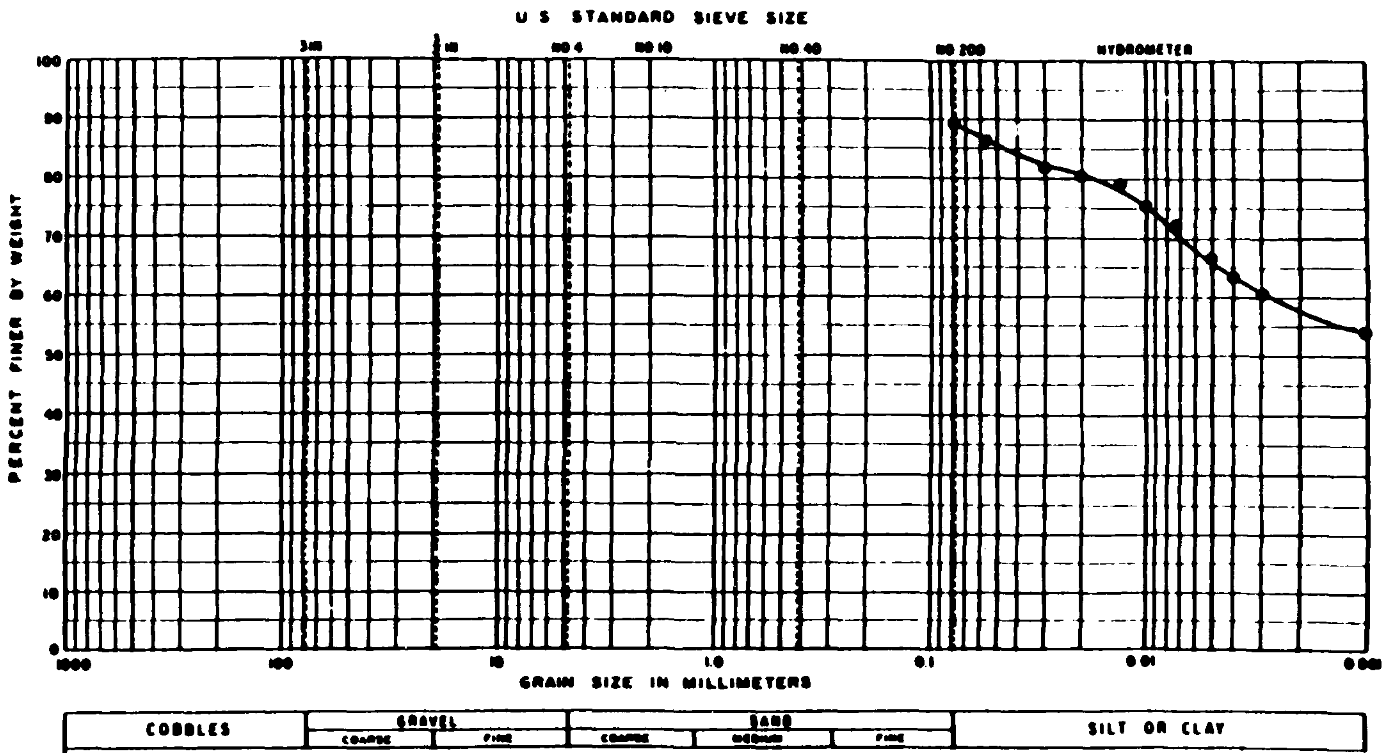
SAMPLE	ELEV-DEPTH	CLASSIFICATION	NAT WC	LL	PL	PI	
1X-3							

GRADATION CURVES



U S STANDARD SIEVE SIZE
HYDROMETER
PERCENT FINER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
SAMPLE
CLASSIFICATION
NAT WC
LL
PL
PI
IX-4
GRADATION CURVES

PLATE A24



SAMPLE	ELEV-DEPTH	CLASSIFICATION	NAT WC	LL	PL	PI	
IX-5							

GRADATION CURVES

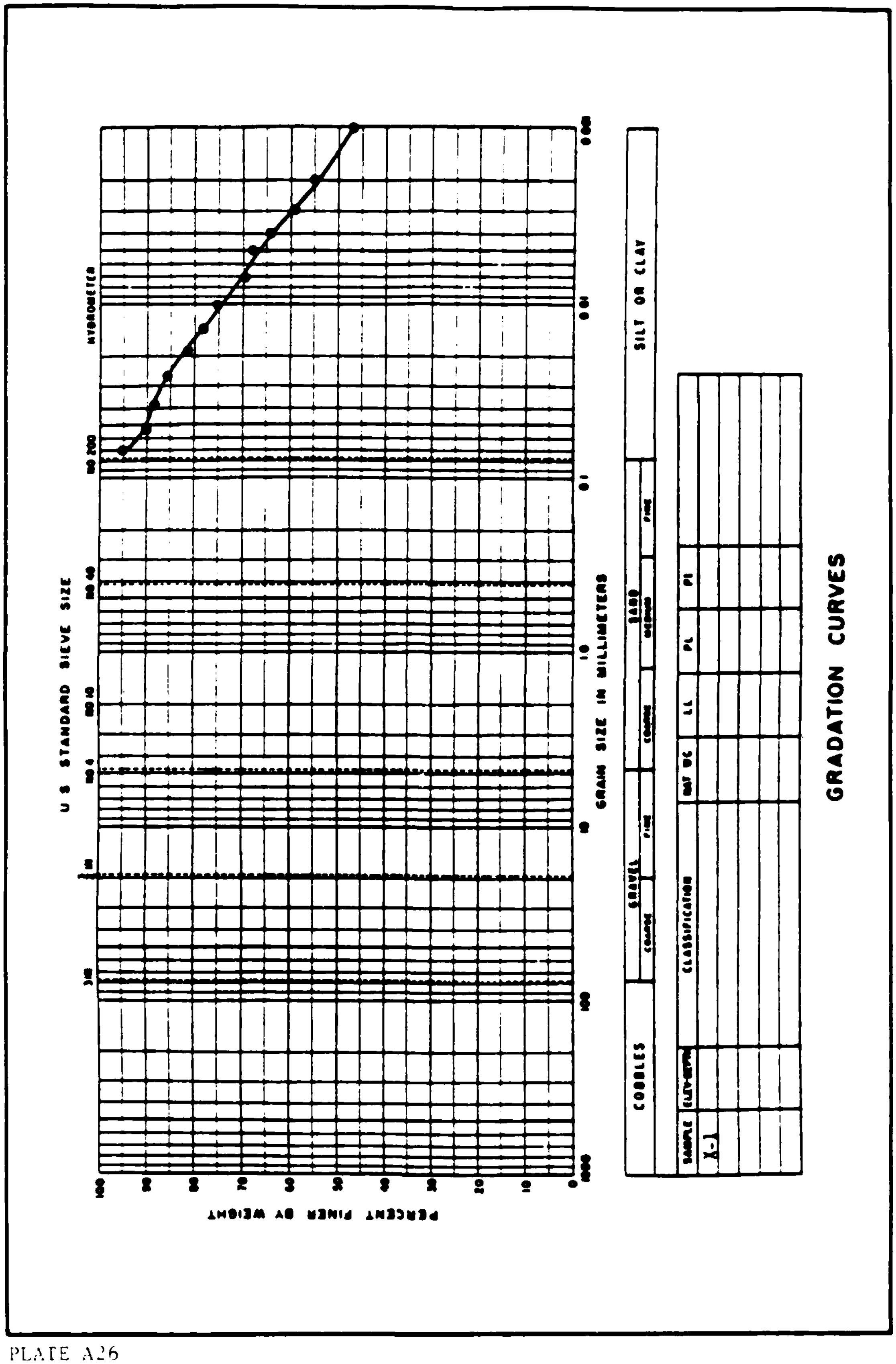
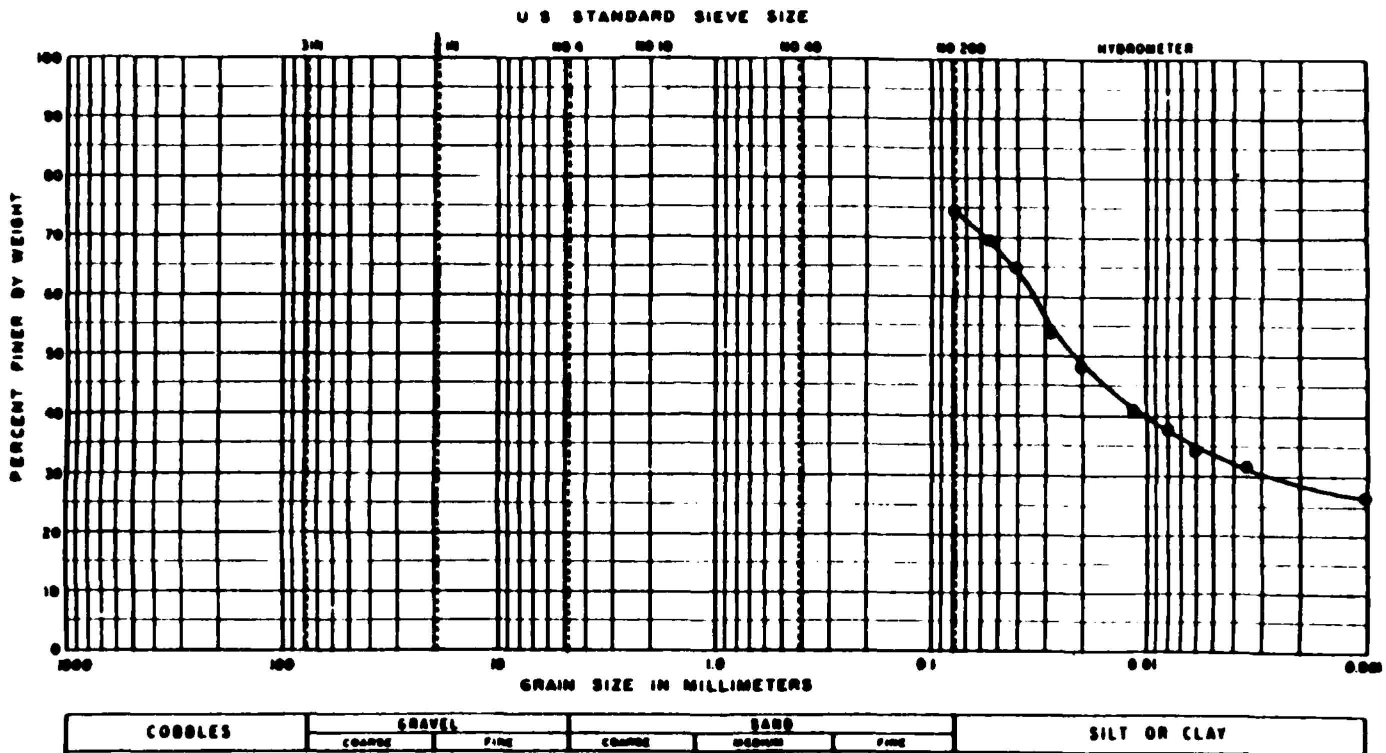
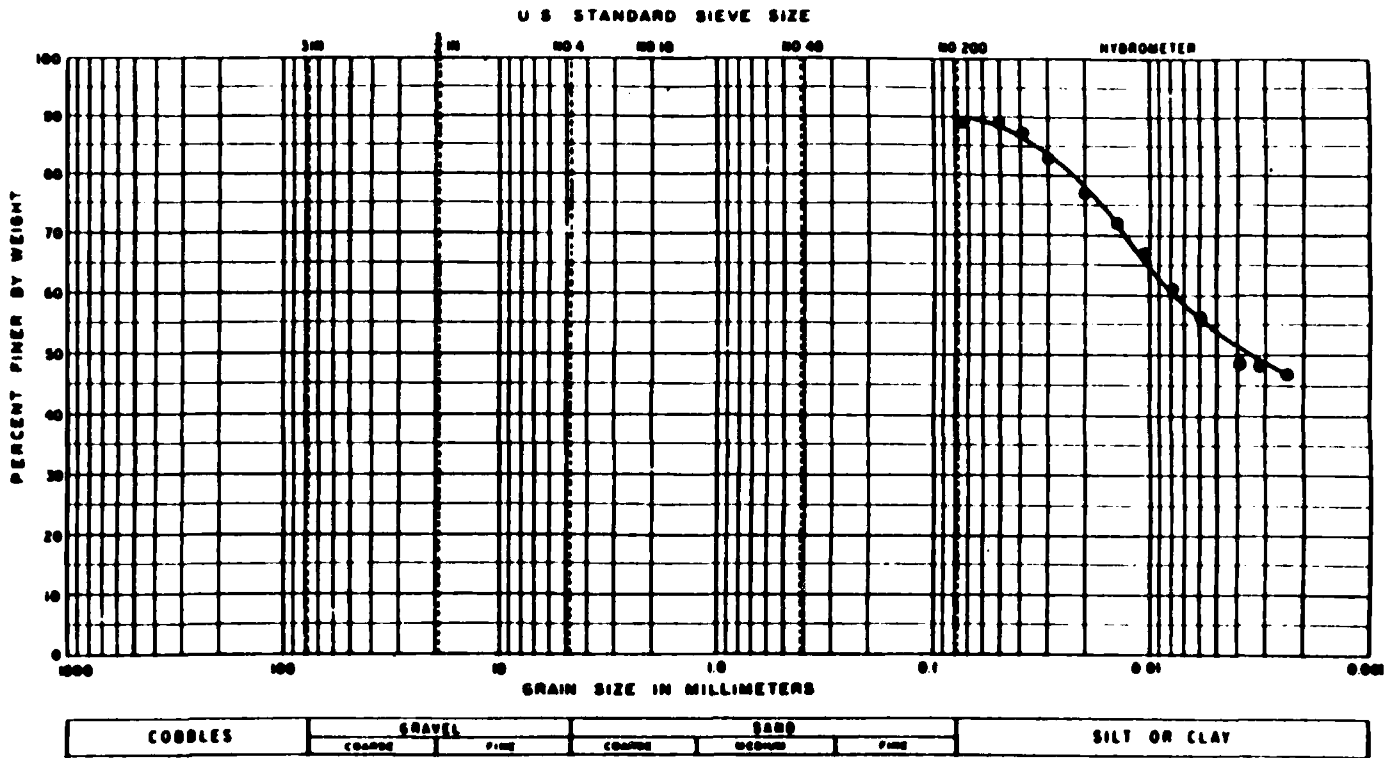

U S STANDARD SIEVE SIZE
HYDROMETER
GRAIN SIZE IN MILLIMETERS
PERCENT FINER BY WEIGHT
COBBLES
GRAVEL
SAND
SILT OR CLAY
SAMPLE
CLASSIFICATION
NAT WC
LL
PL
PI
X-1
GRADATION CURVES

PLATE A26



SAMPLE	ELEV-DEPTH	CLASSIFICATION	NAT WC	LL	PL	PI	
X-2							

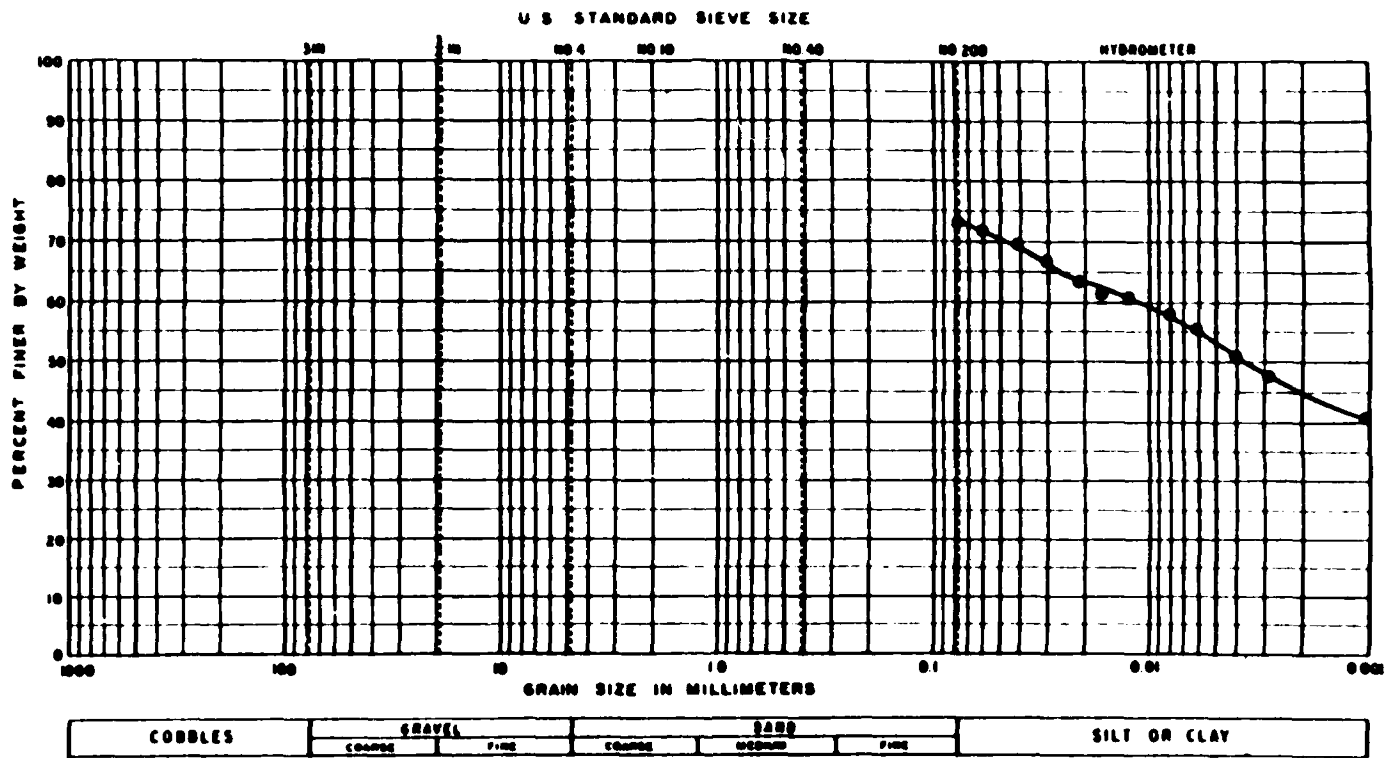
GRADATION CURVES



SAMPLE	ELEV-DEPTH	CLASSIFICATION	NAT WC	LL	PL	PI	
X-3							

GRADATION CURVES

PLATE A28



SAMPLE	ELEV-DEPTH	CLASSIFICATION	NAT WC	LL	PL	PI	
X-4							

GRADATION CURVES

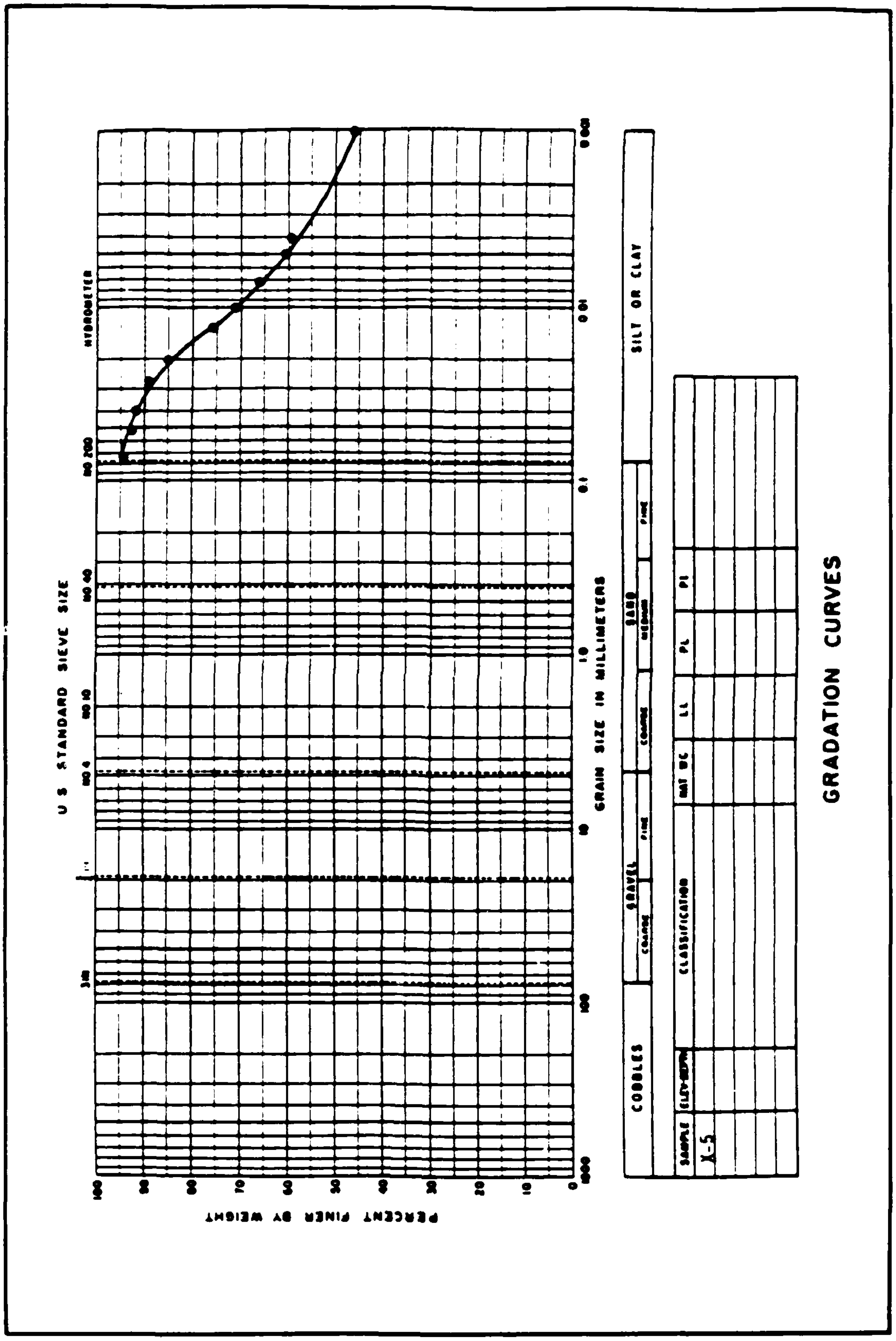
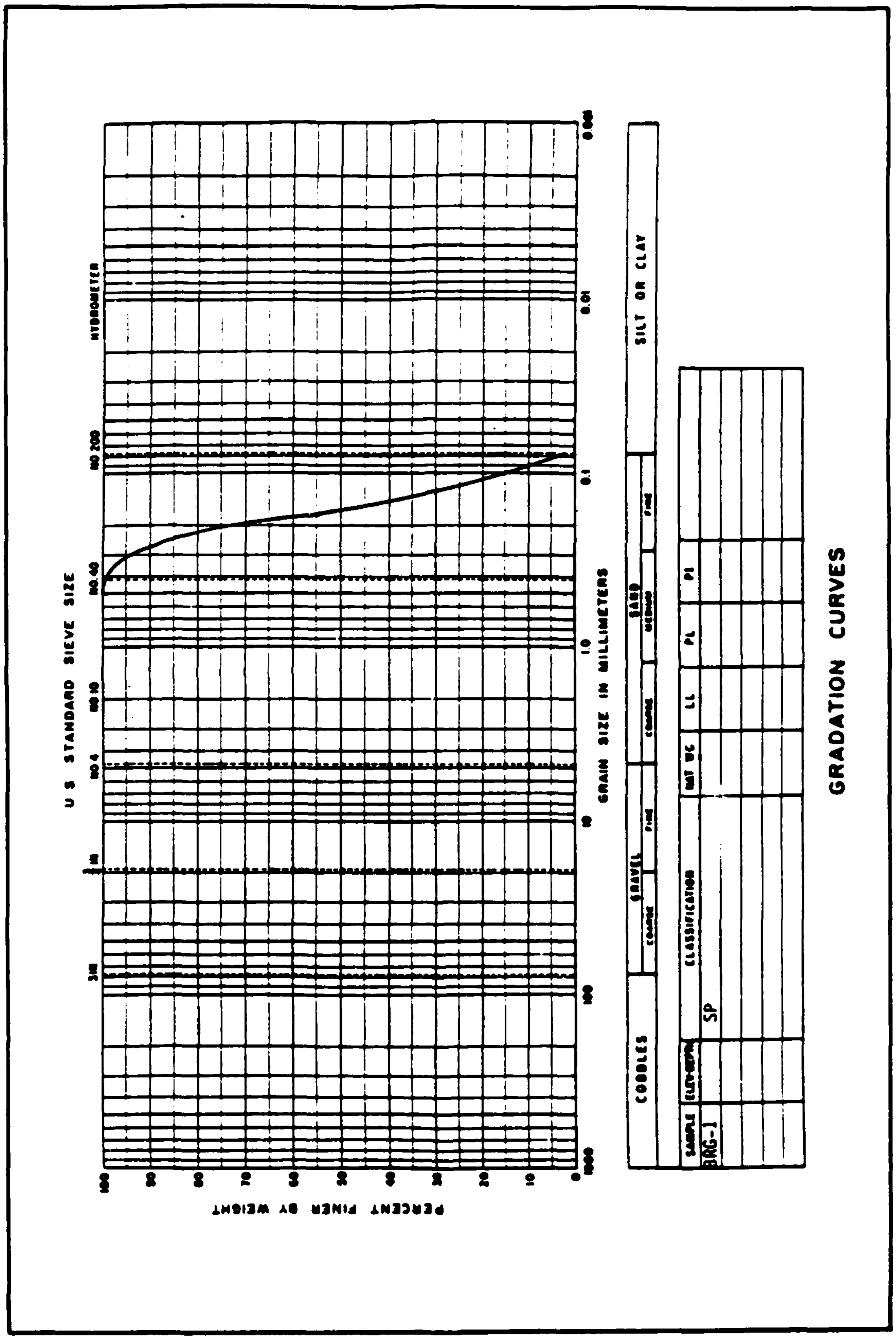

U S STANDARD SIEVE SIZE
3IN
NO 4
NO 10
NO 40
NO 200
HYDROMETER
PERCENT FINER BY WEIGHT
100
90
80
70
60
50
40
30
20
10
0
1000
100
10
1.0
0.1
0.01
0.001
GRAIN SIZE IN MILLIMETERS
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
SAMPLE
ELEV-DEPTH
CLASSIFICATION
NAT WC
LL
PL
PI
X-5
GRADATION CURVES

PLATE A30


U S STANDARD SIEVE SIZE
HYDROMETER
GRAIN SIZE IN MILLIMETERS
PERCENT FINER BY WEIGHT
COBBLES
GRAVEL
SAND
SILT OR CLAY
SAMPLE
CLASSIFICATION
NAT WC
LL
PL
PI
BRG-1
SP
GRADATION CURVES

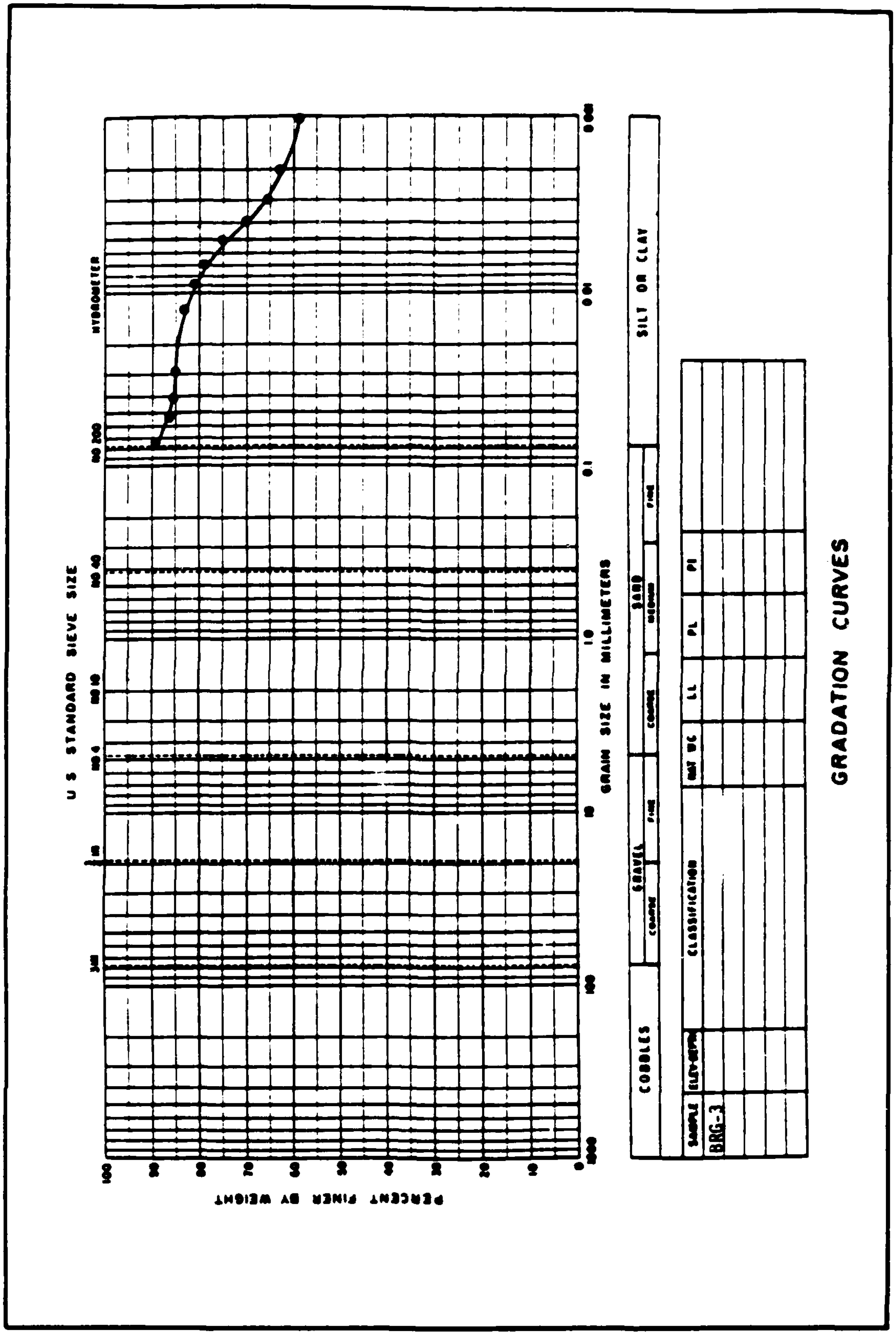
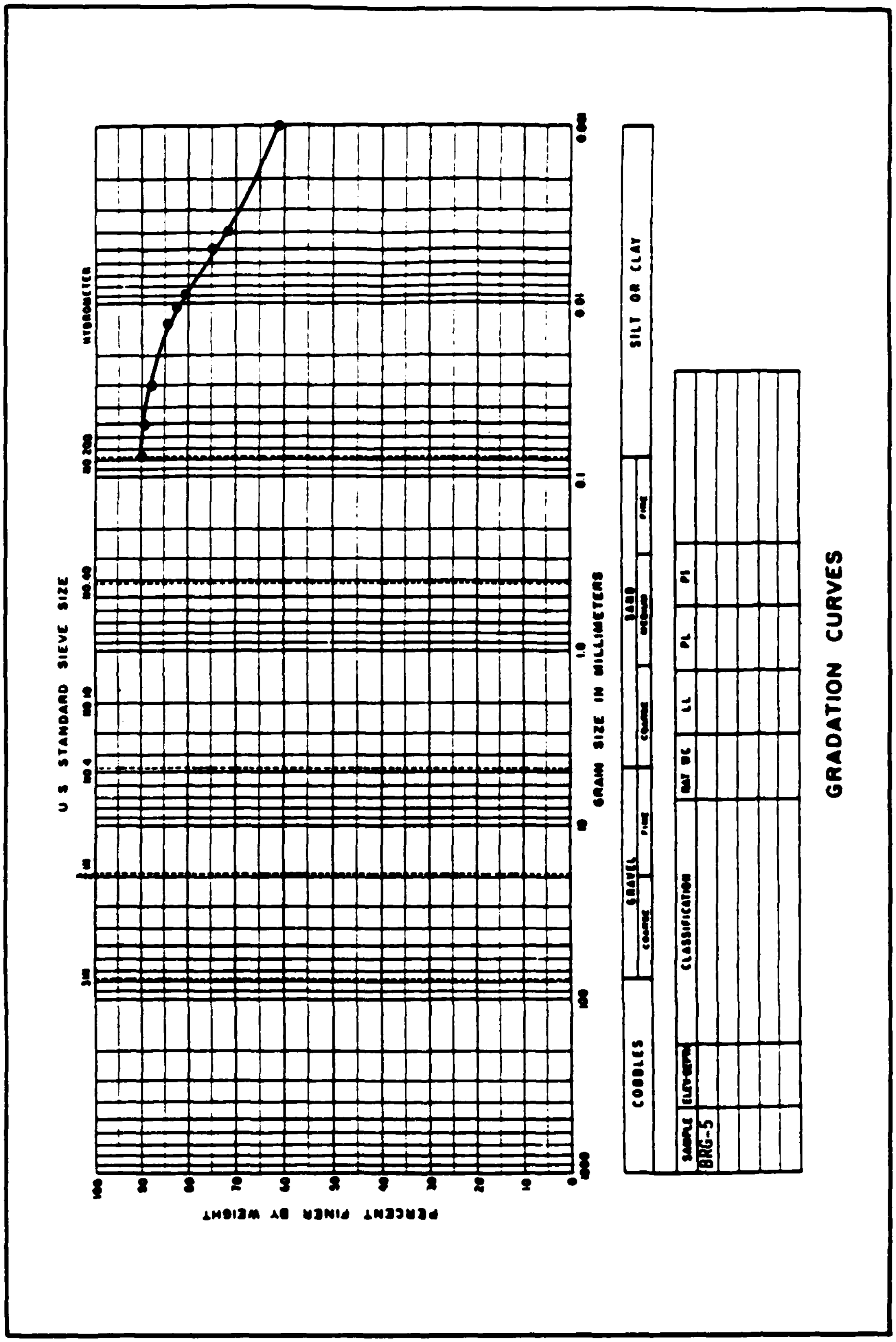

U S STANDARD SIEVE SIZE
NO 4
NO 10
NO 40
NO 200
HYDROMETER
GRAIN SIZE IN MILLIMETERS
PERCENT FINER BY WEIGHT
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
SAMPLE
ELEV-DEPTH
CLASSIFICATION
NAT WC
LL
PL
PI
BRG-3
GRADATION CURVES

PLATE A32



GRADATION CURVES
U S STANDARD SIEVE SIZE
HYDROMETER
NO 4
NO 10
NO 40
NO 200
GRAIN SIZE IN MILLIMETERS
1000
100
10
1.0
0.1
0.01
0.001
PERCENT FINER BY WEIGHT
100
90
80
70
60
50
40
30
20
10
0
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
SAMPLE
CLASSIFICATION
NAT WC
LL
PL
PI
BRG-5

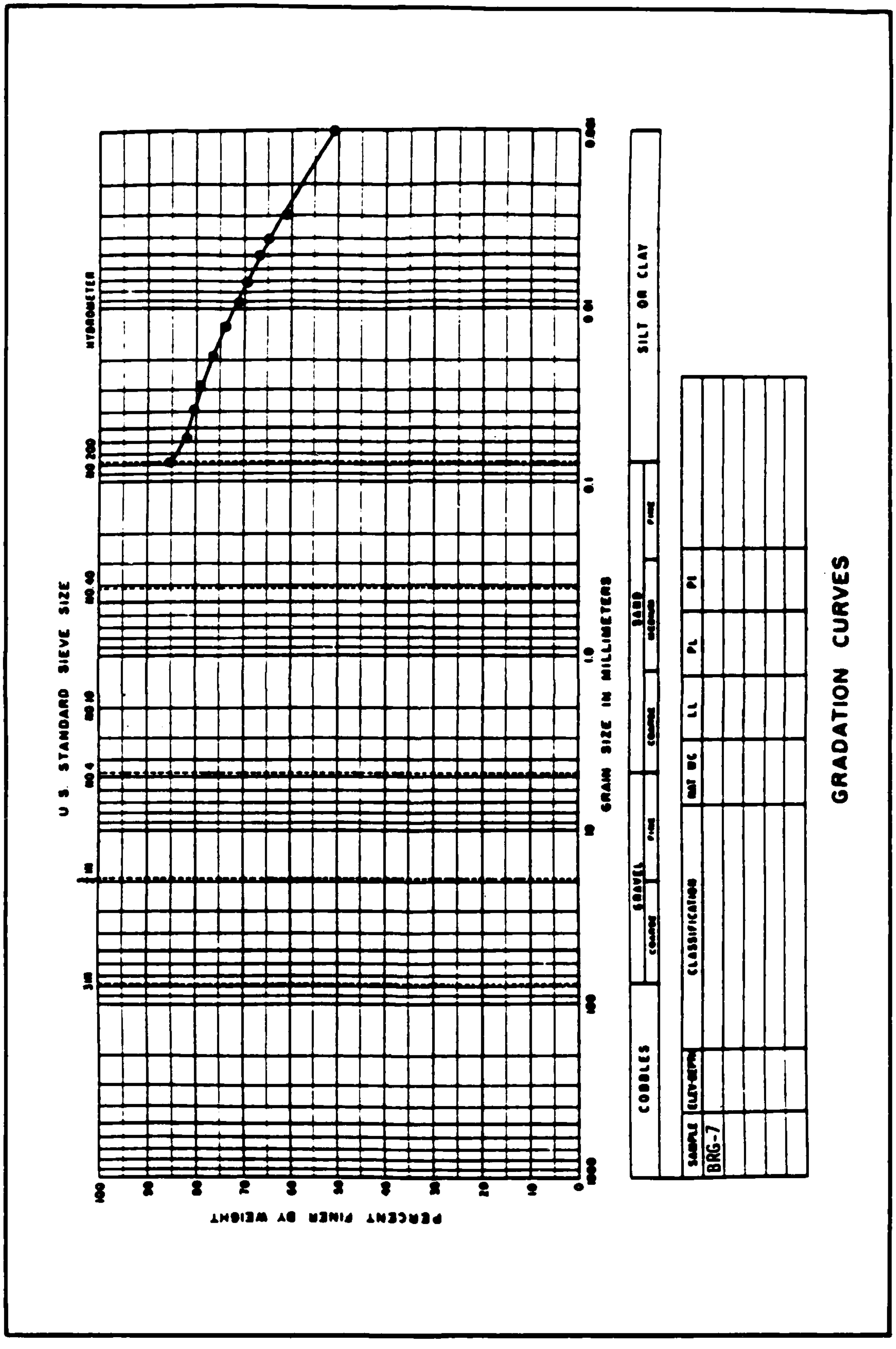
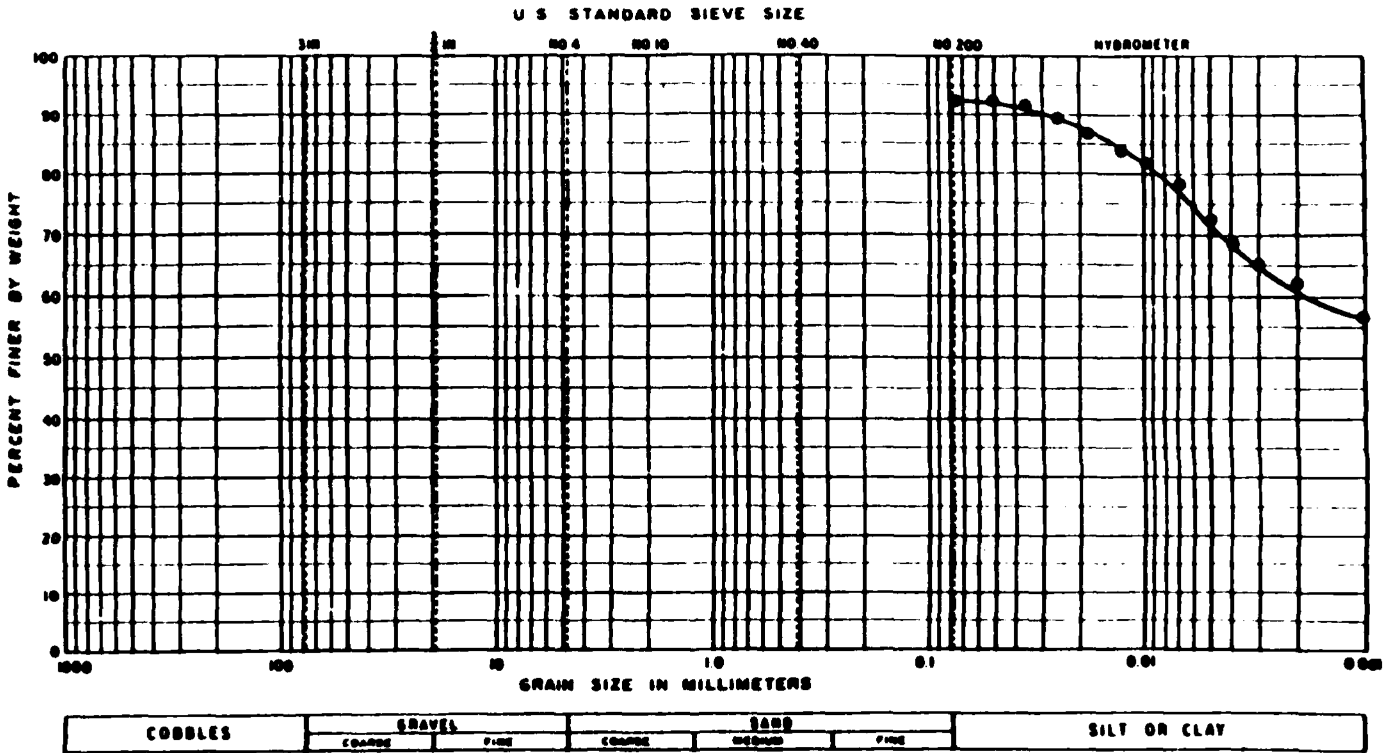
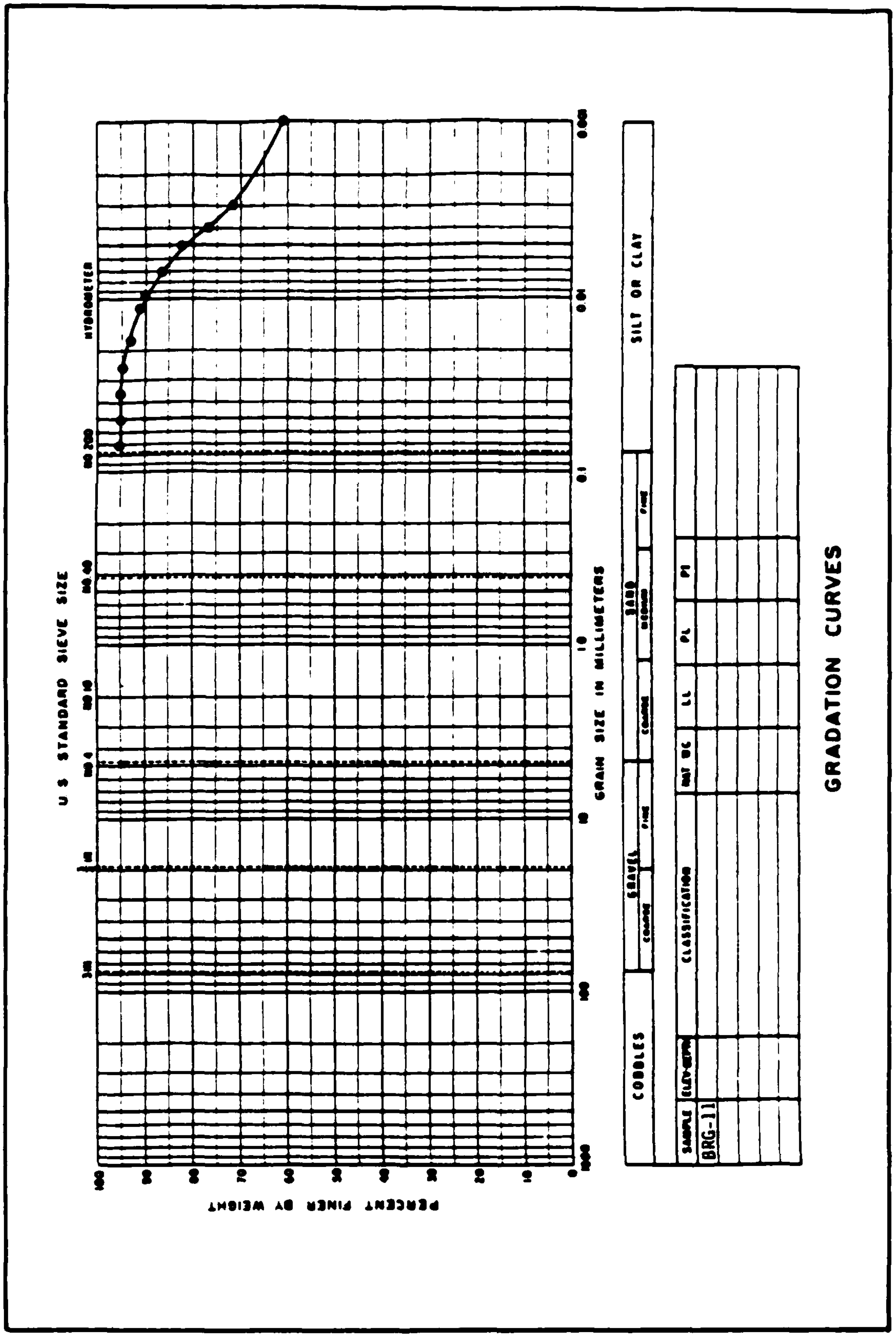

U.S. STANDARD SIEVE SIZE
HYDROMETER
GRAIN SIZE IN MILLIMETERS
PERCENT FINER BY WEIGHT
COBBLES
GRAVEL
SAND
SILT OR CLAY
SAMPLE
ELEV-DEPTH
CLASSIFICATION
NAT WC
LL
PL
PI
BRG-7
GRADATION CURVES

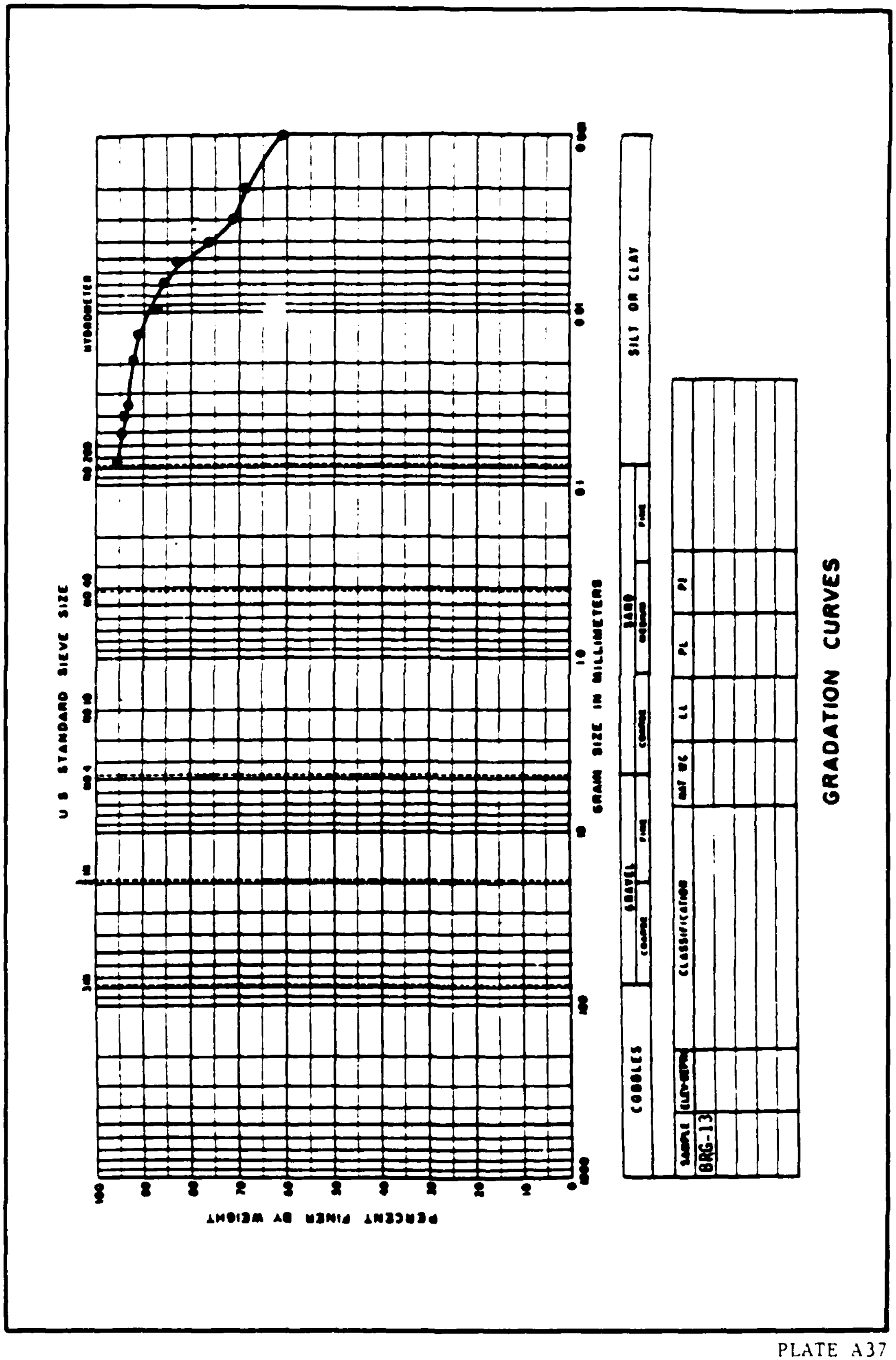
PLATE A34

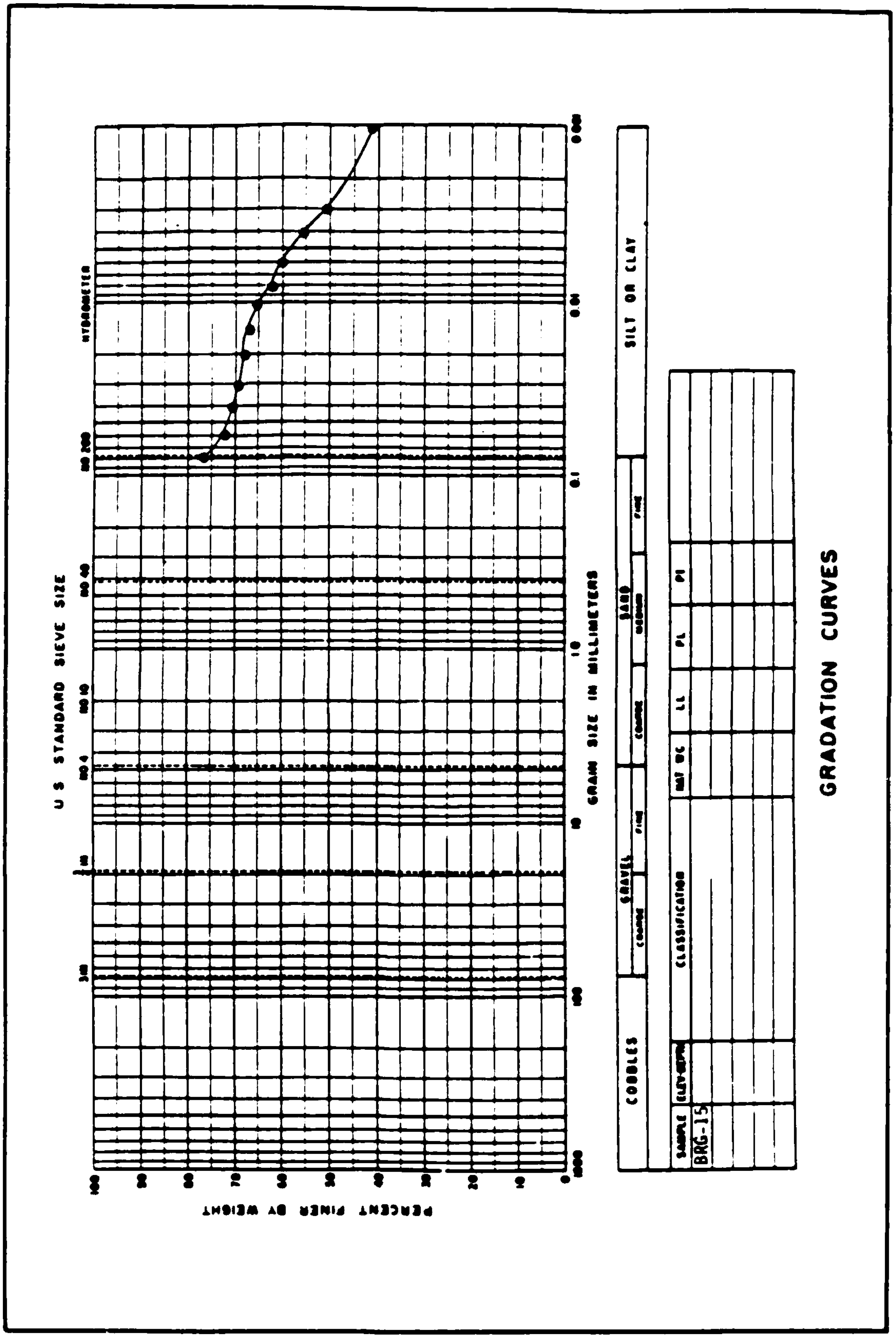


SAMPLE	ELEV-DEPTH	CLASSIFICATION	NAT WC	LL	PL	PI	
BRG-9							

GRADATION CURVES

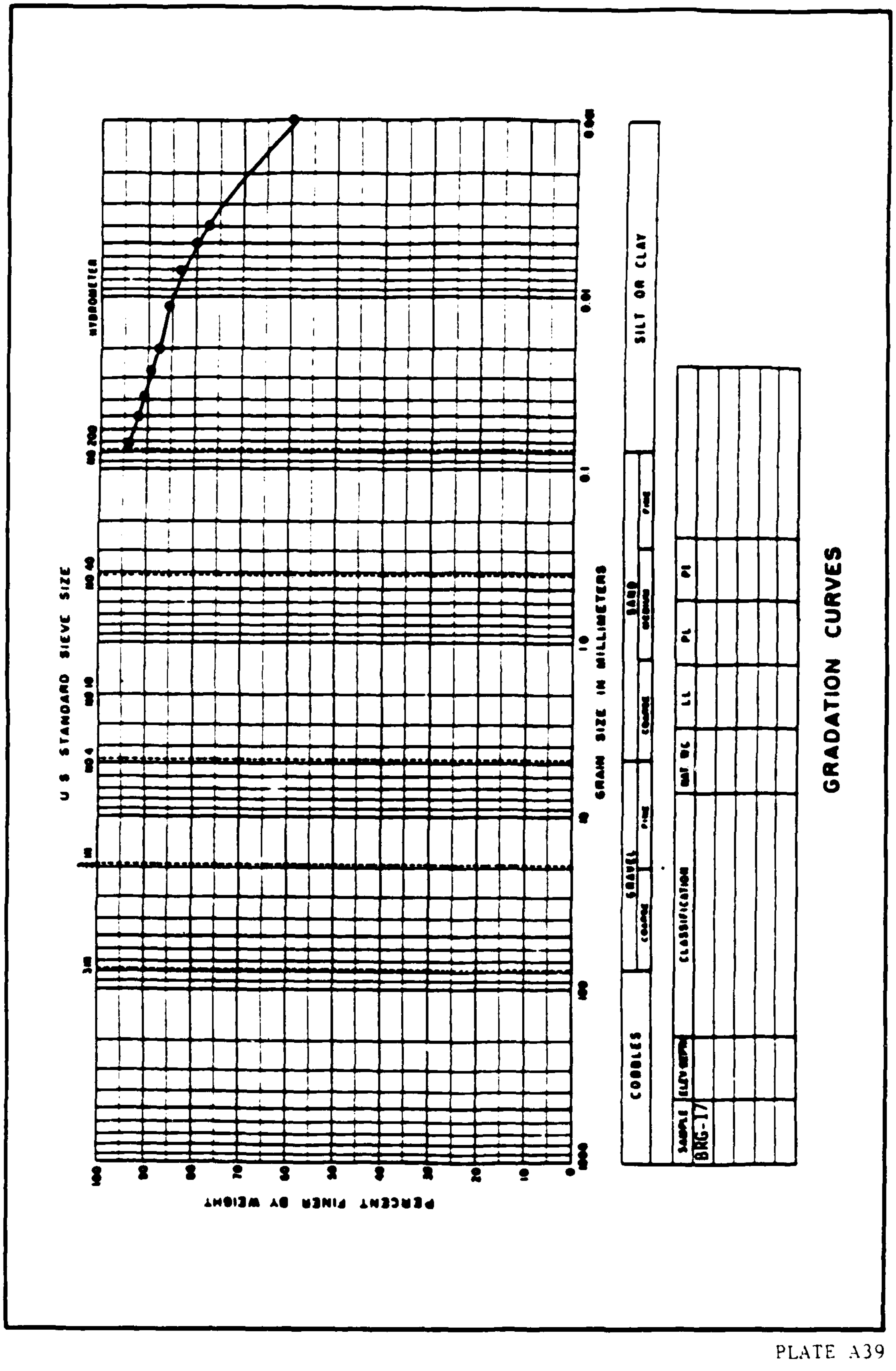

U S STANDARD SIEVE SIZE
HYDROMETER
GRAIN SIZE IN MILLIMETERS
PERCENT FINER BY WEIGHT
COBBLES
GRAVEL
SAND
SILT OR CLAY
SAMPLE
BRG-11
CLASSIFICATION
NAT WC
LL
PL
PI
GRADATION CURVES


U S STANDARD SIEVE SIZE
HYDROMETER
PERCENT FINER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
SAMPLE
ELEV-DEPTH
CLASSIFICATION
NAT WC
LL
PL
PI
BRG-13
GRADATION CURVES



GRADATION CURVES
U S STANDARD SIEVE SIZE
3/4
NO 4
NO 10
NO 40
NO 200
HYDROMETER
GRAIN SIZE IN MILLIMETERS
1000
100
10
1.0
0.1
0.01
0.001
PERCENT FINER BY WEIGHT
100
90
80
70
60
50
40
30
20
10
0
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
SAMPLE
ELEV-DEPTH
CLASSIFICATION
NAT WC
LL
PL
PI
BRG-15

PLATE A38


U S STANDARD SIEVE SIZE
HYDROMETER
PERCENT FINER BY WEIGHT
100
90
80
70
60
50
40
30
20
10
0
1000
100
10
1
0.1
0.01
0.001
GRAIN SIZE IN MILLIMETERS
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
SAMPLE
ELEV/DEPTH
CLASSIFICATION
NAT WC
LL
PL
PI
BRG-17
GRADATION CURVES

APPENDIX B-I: SOURCES OF SHORELINE CHANGE DATA FOR THE STUDY AREA (i.e. TOPOGRAPHIC AND AERIAL PHOTO COVERAGE)

Table B1

Sources of Shoreline Change Data for the Study Area

(i.e. Topographic and Aerial Photo Coverage)

Date	Source
1852, 1858	NOS Chart 206 (Archives)
1933	NOS (by Army Air Corps)
1938 through 1939	Ammann International & Karge Aerial Survey, LTD
1942	USGS Maps and Photo Mosaics
1946	USGS Photo Mosaic
1948	Air Force Photos and Mosaic
1952 through 1953	USDA Photos
1956 through 1957	NOS Photos
1962	Corps Photos
1965	NOS and USDA Photos
1971	NASA Missions 159 and 165 Corps Photos
1978	NOS Photos
1982	Corps Photos
1983	Corps Photos

Table B2

Sources of Hydrographic Data for the Study Area

Date	Source
1929	US Army Corps of Engineers and Odem (1953)
1931	Corps Survey
1932	Corps Survey
1933	Corps Survey
1934	Corps Survey
1937	NOS Chart 1283
1973	Seelig and Sorensen (1973 a,b)
1985	This Study

END

DATE

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